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Abstract

A central question in climate policy is whether early investments in low-carbon technologies are a useful first step towards a more effective climate agreement in the future. We introduce a climate cooperation model with endogenous R&D investments where countries protect their international competitiveness via border carbon adjustments (BCA). BCA raises the scope for cooperation and leads to a non-trivial relation between countries' prior R&D investments and participation in the coalition. We find that early investments in R&D render free-riding more attractive. Therefore, with delayed cooperation on emission abatement and ex-ante R&D investments, the outcome is often characterized by high participation but inefficiently low technology investments and abatement.

1 Introduction

Countries have been struggling for over twenty years to reach an effective international agreement to reduce emissions of greenhouse gases. Still, it is uncertain whether a global treaty that encompasses a large number of participating countries and deep emission cuts for its members can be reached in the future. In the meantime, countries have to make important decisions regarding their technology policy. A central research question is, thus, whether early efforts to bring down the costs of abatement may help to improve the future prospects of cooperation.

In this paper, we analyze the interaction of abatement efforts, R&D investments, and countries' participation decisions in a climate treaty. We treat climate stability and knowledge as two global public goods, and assume that each country can contribute to both of them. In line with Barrett (1994), Carraro and Siniscalco (1993) and other authors from the climate cooperation literature (see, e.g., Finus, 2008, for a survey), we assume that countries decide individually and non-cooperatively whether they want to join a coalition or not. Furthermore, R&D investments are determined *before* countries

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play the membership game. Intuitively, the development of low-carbon technologies is a time-consuming process. Therefore, strategic effects upon later abatement arise when countries determine their R&D investments.

Buchholz and Konrad (1994), Beccherle and Tirole (2011), and Harstad (2012) have shown that these strategic effects can negatively affect welfare. The reason is that countries that reduce their abatement costs more than others by R&D investments will be assigned a higher abatement target at the cooperation stage. This motive for strategic underinvestment is absent in our model because R&D affects all countries' abatement cost functions equally due to its public good nature. However, the positive effect of R&D investments on abatement targets leads to a different problem. It makes *participation* in a future climate coalition less attractive. This effect arises even if countries can determine their R&D efforts cooperatively, as long as there is a delay.[1]

An important feature of our model is that it allows for border carbon adjustments (BCA). This reflects the importance that the topic has received in recent discussions of climate agreements (see, e.g., Böhringer, Balistreri and Rutherford, 2012). BCA is a policy instrument designed to prevent competitive disadvantages for firms located in countries that implement unilateral climate policies. Based on a simple trade model, we assume that firms in signatory countries that export their output to non-signatories are partially exempted from the emissions tax in their home country. Furthermore, import tariffs adjust the total emissions price of firms located in non-signatory countries to the tax raised by signatories.

The introduction of BCA substantially changes the outcome of the climate cooperation game. Similar to R&D, it reduces the abatement cost of signatories (due to export exemptions), which leads to more ambitious abatement targets. One might expect that this makes participation in a coalition less attractive. However, BCA has additional effects that lead to the opposite result. Specifically, the import tariff induces further abatement efforts by the non-signatories and, thus, raises their costs. In combination with the export exemptions, this effectively allows the signatories to 'shift' some of their abatement costs to the non-signatories. Furthermore, signatories receive transfers from non-signatories via the BCA-tariff. These effects make the option to become a signatory more attractive. The endogenous coalition size can, thus, be higher than in a standard cooperation model without BCA. We show that when countries' export shares are large, then often a grand coalition forms in equilibrium. Intuitively, if a single country drops out of a grand coalition, all its exports still go to the remaining signatories. Under BCA, these exports are then subject to import tariffs. This 'cost' of leaving the coalition is large when countries' export shares are large, whereas the benefit of lower abatement costs incurred by the firms that serve the domestic market is then small.

This stabilizing effect of BCA upon cooperation motivated us to integrate BCA into the coalition model. In particular, it allows us to derive a non-trivial relation between countries' R&D efforts and the endogenous coalition size, which is the main focus of this paper. By contrast, we do not explore the effects of climate policies with and without BCA on trade patterns, and the latter will be modeled in a very stylized way.

In our analysis we treat the participation level as a continuous variable and skip the usual integer constraint when countries decide whether to join or leave a coalition.

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[1] Past climate negotiations focused primarily on the issue of emission reductions, and to a lesser extent on the development of low-carbon technologies. A possible reason is that the latter are more difficult to monitor than emission levels.

It turns out that this substantially facilitates the determination of the coalition size. This allows us to use a non-parametric approach, and to carry out most of the analysis without closed form solutions or numerical simulations, on which much of the existing literature has relied. Moreover, we show that this approach is conservative in the sense that it (weakly) underestimates equilibrium participation as obtained in the 'standard' coalition model. Indeed, without BCA the continuous approach would always lead to zero participation. Intuitively, all countries benefit equally from abatement, but costs of abatement are larger for coalition members. Hence, they would always prefer the position of a non-signatory. Accordingly, in the standard approach it is the discontinuity from the integer effect that gives individual countries leverage on the coalitions' abatement target and, thereby, leads to a non-empty coalition. In contrast, in our continuous participation model it is BCA that allows for a positive coalition size.

Our stylized model enables us to tackle the following questions regarding the relation between R&D and coalition formation: Assuming that climate cooperation is currently not feasible – how do countries' prior investments in R&D affect the endogenous participation in a future climate agreement and the amount of emissions reductions achieved? And how do countries – in anticipation of these effects – adjust their R&D efforts?

We show that early R&D efforts are often detrimental to welfare – even if R&D costs are neglected. Intuitively, if the coalition size were fixed, higher R&D investments would lead to a higher abatement target implemented by a coalition. However, this makes it less attractive to become a coalition member in the first place. As a result, participation decreases, which in turn has a negative effect on the coalition's abatement target and welfare. Countries, therefore, have an incentive to reduce their R&D efforts as long as they anticipate that not all countries will participate in a future climate coalition. This underinvestment persists even if countries can cooperate in the R&D dimension (despite the public good nature of R&D in our model). The outcome is thus often characterized by full participation in the climate coalition, but the welfare improvements that this grand coalition achieves are limited due to technology underinvestments.

In an extension of our model (see Section 4), we further show that an alternative outcome may exist, where the free-rider effect manifests itself in the membership game. In this case, countries invest more in R&D, but the welfare gains are now limited due to low participation (as in the classical model by Barrett, 1994). Hence, although our model demonstrates that BCA can significantly improve the prospects of cooperation, a free-rider effect is still present, and it can show up *either* in the R&D-dimension, *or* in the participation dimension.

Related literature

Jaffe, Newell and Stavins (2005) highlight the relevance of technology provision in the area of climate policy, which results in a double public goods problem.[2] Our contribution is closely related to Hong and Karp (2012), who analyze the impact on climate coalition formation of countries' prior R&D efforts that are treated as a pure public good as in our model. In contrast to most of the literature, these authors characterize Nash equilibria of the participation game in mixed strategies, in addition to pure strategy equilibria. The

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[2] Goulder and Mathai (2000) analyze the impact of induced technological change on the optimal time path of the emissions price and abatement in a single-country framework. The authors distinguish between technological change based on R&D efforts, and technological change based on learning-by-doing as a byproduct of abatement activities.

authors find that with mixed strategies, higher investment can lead to higher participation and welfare in equilibrium. By contrast, with pure strategies at the participation stage, higher investment leads to lower participation and may reduce welfare. This latter finding mirrors our results, but the underlying mechanisms are different. Under pure strategies, in Hong and Karp (2012) the stable coalition is just large enough to become active.[3] Hence, higher R&D efforts reduce the stable coalition size because smaller coalitions then become active. In our model, the abatement *per signatory* increases in countries' prior R&D investments (for fixed participation). This enhances the free-rider incentive and, via reduced participation, lowers welfare.

Barrett (2006) analyzes technology provision in a framework that addresses the double public goods problem of knowledge provision and abatement by a system of two treaties: a technology and an adoption treaty. He considers 'breakthrough technologies' and shows that the free-rider incentive undermines the scope of cooperation, unless the new technologies exhibit 'increasing returns to adoption' (which the author argues is unlikely to be the case for the most relevant low-carbon technologies).[4] Similar to that paper, our model allows for the possibility of an early R&D coalition (although the non-cooperative R&D case that we also consider is probably more relevant). An emission abatement coalition forms only at a later stage, taking countries' prior R&D investments as given. In a simultaneous move game without cooperation, Heal and Tarui (2010) analyze how the degree of technology spillovers affects countries' investment decisions in low-carbon technologies.[5]

Various modifications of climate cooperation models that are related to ours have been introduced in the literature. Finus and Maus (2008), e.g., assume that signatories consider only a fraction of their damages when choosing their abatement target. This target is, thus, less ambitious, and the authors show that this can positively affect the coalition size and welfare. In our model, similar effects are obtained endogenously via countries' R&D choices. Barrett (1997) assumes that countries can link climate agreements to trade issues, which allows the signatories of a climate treaty to impose punishments on non-signatory countries. These punishments make the option to join the treaty relatively more attractive, which increases the scope for cooperation.[6] While punishments via trade sanctions may not be in conformity with WTO rules, the BCA measures that we propose are a softer instrument with the goal of leveling the playing field for international trade when some countries are more active in the area of climate protection than others. Hence,

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[3] Unlike in our model, due to their assumption of a linear cost and benefit structure, abatement decisions are at the boundary in Hong and Karp (2012). Hence, when the coalition becomes active, all members abate up to their maximum abatement capacity, whereas when one member drops out of the stable coalition, signatories do not abate at all. (A similar property is obtained also in Barrett (2006), where signatories only adopt a 'breakthrough technology' if the coalition size is large enough.) In their investment game, Hong and Karp (2012) assume binary decisions (each country can either invest or not invest at the prior R&D stage). In our model each country's R&D effort is a continuous choice.

[4] Hoel and de Zeeuw (2010) show that more optimistic results can be obtained when the fixed development cost in Barrett (2006) is replaced by a continuous adoption cost function that declines in the total R&D effort.

[5] They find that R&D investments can be higher than under first-best when marginal abatement costs are increasing in R&D efforts and technology spillovers are small. In our model, we focus on the case of knowledge as a pure public good (large technology spillovers), and assume that marginal abatement costs are declining in the aggregate R&D effort. The counter-intuitive result of Heal and Tarui (2010) can, thus, not arise.

[6] Hoel and Schneider (1997) assume that countries that stay out of a climate coalition incur a social cost of non-cooperation, which also tends to stabilize cooperation.

they may be easier to justify than trade sanctions. Böhringer, Fischer, and Rosendahl (2014) compare different policy instruments against carbon leakage and find that BCA ranks first in cost-effectiveness. They also analyze the interaction between BCA and coalition sizes, but the latter is not determined endogenously as in our paper.

Our continuous membership approach has similarities with Hong and Wang (2012), who analyze technology adoption by small countries in a prior R&D stage. These authors assume that the participation decision of an individual country cannot influence the behavior of the coalition because it is so small. Also in our model, the continuity in the coalition size makes each country too 'small' to exercise leverage on others. Hong and Wang (2012) emphasize the role of social preferences and sanctions as drivers for small countries to join a coalition, modeled as a fixed cost of nonparticipation.[7] In our model, the incentives of a country to join a climate coalition are obtained endogenously from the effects of BCA. Although we do not assume that countries are small at the R&D stage, our continuous membership approach in conjunction with BCA is applicable also for small countries.

Harstad (2012) uses a model with infinitely many periods to study binding climate agreements under dynamic interaction. Instead of a single climate agreement, countries negotiate agreements repeatedly. Similar to our model, countries can invest in R&D, and then cooperate in their abatement efforts. To obtain tractable results, Harstad (2012) assumes an additive structure, in which R&D has no effect upon the marginal costs of abatement. Beccherle and Tirole (2011) allow for a more general relation between R&D investments (or other types of early efforts) and abatement costs, but do not account for repeated interaction. Our model is closely related to this paper. However, while Beccherle and Tirole (2011) focus on the effects of bargaining and abstract from the free-rider incentive, we endogenize participation in the climate coalition. Battaglini and Harstad (2014) also analyze participation in climate agreements, and allow for an endogenous length of the commitment period in a framework with repeated interaction. The authors find that countries' inability to specify R&D efforts in low-carbon technologies in a climate treaty may raise the efficiency of the final outcome.

The remainder of this paper is organized as follows. In Section 2, the cooperation model with BCA is introduced, and equilibrium participation and abatement are analyzed. Section 3 endogenizes countries' R&D efforts, and shows that countries often underinvest in R&D in order to raise participation. Section 4 considers an extension of the model regarding the abatement strategies of coalition outsiders. All proofs are relegated to the Appendix.

2 Coalition model with BCA

Consider N symmetric countries, indexed $i = 1, ..., N$, that regulate their emissions via carbon prices ($p_i \geq 0$ is the price implemented by country i), and play the following climate cooperation game: First, countries non-cooperatively decide whether to join a climate treaty. Second, countries simultaneously decide about their climate policies. Non-signatories choose these individually and non-cooperatively, while signatories maximize their joint welfare. We now extend this standard model by introducing BCA.

The main justification for BCA is to balance distortions in countries' international competitiveness. These arise if some of them unilaterally contribute more to the global

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[7] A similar approach was introduced by Hoel and Schneider (1997).

public good of climate stabilization than others. We focus on 'full BCA' which results in a destination-based carbon pricing (e.g., Böhringer et al., 2012). Specifically, emissions embodied in exports to a country with a lower carbon price are taxed by the exporting country only at the price of the foreign country. Moreover, emissions embodied in imports from a country with a lower carbon price are subject to a tariff such that the overall carbon tax of the foreign firm matches that of the importing country.

The partial export exemptions reduce abatement of coalition members, while the BCA-tariff raises abatement of non-signatories. Moreover, we assume that BCA tariff revenues accrue to the country that levies the tariff, and thus add to the welfare of signatories.[8] Intuitively, all three effects tend to stabilize cooperation. As a result, the range of coalition sizes in our model is substantially larger than in the standard model, where participation does not exceed three countries for typical specifications of benefit and abatement cost functions (Barrett, 1994). This is a basic prerequisite for analyzing the effects of R&D investments on the coalition size in Section 3.

Since countries are ex-ante identical, it is natural to assume that their export shares are the same, and that exports go in equal proportions to all other countries. In order to keep the analysis tractable, we assume that these export shares of the 'polluting goods' are not affected by climate policies *provided that BCA is implemented.* This assumption can be interpreted as the most parsimonious way to capture the idea that BCA achieves its goal of leveling the playing field for trade between signatories and non-signatories. Calibrated numerical simulations show that BCA may indeed constitute an effective instrument for maintaining competitiveness of energy-intensive and trade-imposed (EITE) industries. In a model comparison of the Energy Modeling Forum that considers the effect of unilateral CO_2 emission reductions by 20%, the loss of EITE production in abating countries falls on average from 2.8% to roughly 1% (Böhringer et al., 2012, p. 102) if BCA is implemented. Also the meta-analysis in Branger and Quirion (2014) confirms that BCA successfully corrects for the output loss of EITE industries which is caused by climate policies.[9]

Constant export shares can also be deduced from a highly stylized trade model by assuming inelastic demand for differentiated tradeable goods. We now sketch such a model, and use it to derive countries' abatement cost and payoff functions under BCA. A formal description of this model is given in Appendix B. However, we wish to emphasize that the subsequent analysis depends on the assumption of constant export shares, but *not* on the specific microfoundation that has been chosen mainly for its simpleness. In more elaborate models, additional effects would arise, e.g., related to the terms-of-trade. Analyzing such effects would require a substantially more detailed description of the economy, which would render the analysis intractable, especially when we later endogenize R&D efforts.[10]

Suppose that in each country there is a representative consumer who desires to consume a certain bundle of differentiated imported and domestic polluting goods, as well

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[8] This is the default scenario that has been used in the model comparison of the Energy Modeling Forum (Böhringer et al., 2012).

[9] The authors find that this effect is larger in computable general equilibrium models than in partial equilibrium models.

[10] Recently, Eichner and Pethig (2013) integrated international trade in a standard coalition model. However, they rely on numerical simulations to solve their model, and do not account for endogenous R&D efforts and BCA. See also Böhringer, Lange, and Rutherford (2014) for an analysis of leakage and terms-of-trade motives of emission pricing.

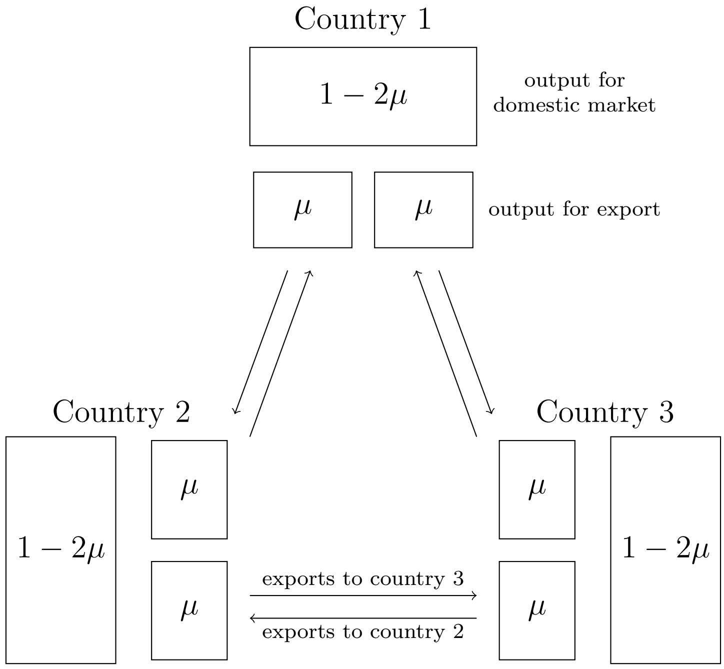

Figure 1: Production and trade flows of polluting goods in an example with 3 countries

as a non-polluting numeraire good (all goods are tradeable). In each country, the (representative) consumer has the same ideal consumption level for each of the differentiated polluting goods supplied by firms located in foreign countries (remember that countries are ex-ante symmetric). Specifically, let $z \min\{\mu, x_{ij}\}$ be the utility that the consumer in country i obtains from consuming x_{ij} units of the polluting good supplied by the foreign country $j \neq i$ (utility is additively separable). If the marginal utility z and the consumer's wealth are sufficiently high, then in each country the consumer demands μ units of the polluting goods imported from each of the other countries $j \neq i$. Thus, consumption patterns are, in effect, fixed. Moreover, in each country the total consumption of imported polluting goods is $(N-1)\mu$.

Since each country i imports μ units of a polluting good from each of the other countries $j \neq i$, the parameter μ can be interpreted equivalently as exports of country i to *each* of the other countries. Thus, $(N-1)\mu$ are also a country's total exports. Normalizing a country's overall consumption and production of polluting goods to 1, the remaining output of the polluting sector in country i, $1-(N-1)\mu$, is consumed domestically. Note that, due to this normalization, $\mu \in [0, 1/(N-1)]$. We slightly narrow this range by assuming $\mu < 1/N$, which simply says that a country's exports to each *individual* other country do not exceed its production for the domestic market.

Figure 1 illustrates the production and trade flows of polluting goods for the case of three countries. The output of the polluting good produced by country i that is consumed domestically is, thus, $1-2\mu$. Furthermore, each country produces an amount μ of polluting good for export to *each* of the other countries. Since the total output of each country is normalized to 1, the total amount of polluting goods that is consumed in each country is also 1.

Now consider the situation where some countries unilaterally implement a price on carbon emissions. By construction, consumption patterns are fixed, but firms in countries with carbon prices would have an incentive to relocate to countries without carbon prices.[11] Thus, trade patterns would change substantially in the absence of BCA, provided that relocation costs are not too high. By contrast, with BCA the carbon price that a firm faces depends only on where the good is *consumed*, but not on where it is produced. This eliminates firms' relocation incentives so that trade flows and, therefore, the export share μ remains unchanged if (and only if) BCA is implemented between all countries (as we assume throughout the paper).

In the above model, carbon pricing does not lead to output contraction of polluting goods. Instead, we assume that each firm has access to an abatement technology. In particular, let a_{ij} be the *abatement intensity* (abatement of emissions per unit of output) of a firm located in country j that exports to country i. We assume that a firm's abatement costs are proportional to the firm's output, and increasing in a_{ij}. Specifically, abatement costs of a firm per unit of output are $c(a_{ij})h$, where h is a scaling parameter.[12] We assume that $c(\cdot)$ satisfies the standard assumptions $c'(\cdot) > 0$, $c''(\cdot) > 0$ for all $a_{ij} > 0$, as well as $c(0) = c'(0) = 0$ and $c''(0) \geq 0$.

BCA leads to destination-based carbon pricing so that all firms that sell their goods in country i face the same price p_i. Hence they all choose an identical abatement intensity according to $p_i = c'(a_{ij})h$. Given that consumption of polluting goods in country i is normalized to 1, total abatement *induced* by country i's carbon price is $a_i \equiv a_{ij}$. It follows that

$$p_i = c'(a_i)h \tag{1}$$

determines a_i as a function of p_i as in a standard model of climate cooperation. Hence, we will refer to a_i as country i's *abatement target.* Unlike in other models, however, not all of this abatement takes place in country i. Firms located in country i undertake only a fraction $1-(N-1)\mu$ of the total abatement induced by country i's carbon price. This is the output of the firm that is located in country i and produces for domestic consumption (see Figure 1), while the exporting firms are subject to foreign carbon prices.

Let k denote the number of countries that join a climate coalition. Using again countries' symmetry, all k signatories (subscript s) and all $N-k$ non-signatories (subscript n) will choose identical carbon prices of p_s and p_n, respectively. This yields the following expression for the welfare of a signatory:

$$\Pi_s = bA - (N-k)\mu c(a_n)h - [1-(N-k)\mu]c(a_s)h + t_s. \tag{2}$$

The first term on the right-hand side are the benefits of climate polices, which are assumed to be linear in aggregate abatement, denoted $A \equiv \sum_i a_i$.[13] The second term reflects that exports of polluting goods to the non-signatories, $(N-k)\mu$, are subject to their carbon price p_n and, therefore, associated abatement follows from $p_n = c'(a_n)h$. The remaining output of country i's polluting good, $1-(N-k)\mu$, is subject to the carbon price of signatories, p_s, and associated abatement follows from $p_s = c'(a_s)h$. Finally, t_s are the net transfers of BCA tariffs to a signatory (see below). Similarly, welfare of a

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[11] Firm relocation (or more generally the relocation of productive activities) is an important channel of 'carbon leakage' (e.g., Babiker, 2005).

[12] The parameter h will be specified further in Section 3 where countries' R&D efforts are endogenized.

[13] This simplification is widely used in the literature (e.g., Barrett, 2006). Finus et al. (2006) show that discounted climate damages that are linear in emissions are indeed a good approximation of the figures in the RICE model (Nordhaus and Yang, 1996), although damages are non-linear in temperature change.

non-signatory is

$$\Pi_n = bA - k\mu c(a_s)h - (1-k\mu)c(a_n)h + t_n, \tag{3}$$

which reflects that an output share of the country's polluting good of $k\mu$ is sold to signatories, and the remaining output, $(1-k\mu)$, to non-signatories.

It remains to determine BCA-induced transfers. Denote baseline emissions per unit of output by $\bar{E}$. Given that the output of polluting goods is normalized to 1, these are also the baseline emissions per country. In order to avoid corner solutions, we assume that they *always* exceed equilibrium abatement a_i. Each non-signatory has to pay the carbon tariff, $p_s - p_n$, for its emissions embodied in exports to the k signatories, $k\mu(\bar{E} - a_s)$. It follows that

$$t_n = -k\mu(\bar{E} - a_s)(p_s - p_n). \tag{4}$$

Such transfers are paid by $N-k$ non-signatories, and shared among k signatories, yielding

$$t_s = (N-k)\mu(\bar{E} - a_s)(p_s - p_n). \tag{5}$$

Finally, observe that for $\mu = 0$ – i.e., if there is no trade and, therefore, no BCA – the welfare function has the 'standard' form $\Pi_i = bA - c(a_i)h$.

2.1 Choice of abatement

We now analyze countries' emission reduction policies. From (1), these can be described equivalently as choosing a carbon price p_i, or an abatement target a_i. In order to produce clean results that do not depend on specific functional forms, we make the following simplifying assumption.

Assumption 1. Non-signatories do not regulate their emissions, i.e. $p_n = 0$.

In a setting with identical countries and N being sufficiently large, the effect of any individual country on climate damages is small and, therefore, also its incentive to reduce emissions. Moreover, establishing a domestic emissions control scheme is likely to be accompanied by some fixed costs, and potentially faces opposition from lobbying groups (see Sterner and Isaksson, 2006). Hence, a government of a country that is not part of a climate coalition may well decide against the implementation of domestic climate policies.

In line with this, the assumption that non-signatories do not regulate their emissions has also been employed in other papers on BCA (e.g., Böhringer et al., 2014), and in coalition models with binary abatement choices, where countries either abate or not (e.g., Barrett (2001), Hong and Karp (2012)).[14] It also results endogenously if one assumes a continuum of countries (e.g., Martimort and Sand-Zantman, 2013). Then each individual country has no benefits from abatement because it is infinitesimally small.

Nevertheless, in our model Assumption 1 imposes a suboptimal policy upon non-signatories because $c'(0) = 0$. Relaxing the assumption that non-signatories do not regulate their emissions adds additional strategic considerations that would render the following non-parametric analysis intractable. Therefore, we skip the discussion of these additional effects until Section 4, where we assume a quadratic specification of the cost

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[14] For another coalition model where non-signatories always abate zero, see Karp and Simon (2013, p. 330). It is based on assuming marginal costs that are constant up to a capacity constraint.

function and analyze the model numerically. This allows us to drop Assumption 1 and to show that our main qualitative results are robust.

The assumption $p_n = 0$ implies that $a_n = 0$. Thus, to simplify notation, in the following we write p instead of p_s, and a instead of a_s. The welfare function of a signatory (2), respectively of a non-signatory (3), then becomes (using (4) and (5))

$$\Pi_s(k,a) = bA - (1-\mu(N-k))c(a)h + \mu(N-k)p(\bar{E}-a), \text{ and} \tag{6}$$

$$\Pi_n(k,a) = bA - k\mu c(a)h - k\mu p(\bar{E}-a). \tag{7}$$

Turning to emission reduction policies of signatories, we adopt the standard assumption that they choose the carbon price p so as to maximize their joint welfare. However, in our model welfare includes BCA-induced transfers from non-signatories to signatories. This leads to an additional strategic effect as signatories could raise tax revenues from firms outside the coalition by setting a higher carbon price. Such a strategic manipulation of environmental policies in order to raise income from BCA would probably violate WTO rules. This is reinforced by the fact that the coalition acts like a cartel.[15] Therefore, we make the following assumption.

Assumption 2. Coalition members do not adjust their emission reduction policy with the aim to raise income from BCA.

Given this assumption, signatories ignore effects on BCA-induced transfers (see the last term in (6)) when choosing their abatement target, a. Hence, maximizing welfare of a coalition of size k yields the first-order condition (the second-order condition is trivially satisfied)

$$bk = [1-\mu(N-k)]c'(a^*)h. \tag{8}$$

This defines the equilibrium abatement target, a^*, as a function of k, yielding $a^*(k)$ and $A^*(k) = ka^*(k)$. We thus obtain the well-known property that coalition members choose abatement such that their aggregated marginal benefit, bk, equals marginal cost. However, the latter is lower than in a situation with no trade ($\mu = 0$), where the first-order condition would simplify to $bk = c'(a^*)h$. The reason is that a signatory's exports to the $N-k$ non-signatories, $\mu(N-k)$, are exempted from the carbon price. This reduces signatories' costs of implementing a given abatement target; hence they choose a higher abatement target than without BCA.[16] Intuitively, BCA shifts part of the abatement costs to non-signatories, which gives signatories an incentive to set a higher emissions price.

Raising the coalition size reduces this effect, ceteris paribus inducing less abatement. However, as k rises more damages are internalized, inducing more abatement. The following result shows that the latter effect dominates.

Lemma 1. *The abatement target $a^*(k)$, and hence total abatement, $A^*(k) = ka^*(k)$, are strictly increasing in participation, k.*

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[15] The fear that BCA could be used for back-door trade policy has indeed been emphasized in the literature, and is one of the main political obstacles for its implementation (see Bhagwati and Mavroidis (2007) for a discussion of legal and policy aspects).

[16] The higher abatement target is implemented via a higher emissions price. The emissions price of signatories is (using (8)): $p^* = c'(a^*)h = bk/(1-\mu(N-k))$.

2.2 Membership game

We now turn to the first stage of the game, where each country decides whether to become a coalition member. Note that this decision will take into account how BCA-transfers affect welfare. The usual approach is that the equilibrium participation level k is constrained to be an integer that satisfies the following conditions of 'external' and 'internal' stability:

$$\Pi_n(k, a^*(k)) \geq \Pi_s(k+1, a^*(k+1)), \text{ and } \Pi_s(k, a^*(k)) \geq \Pi_n(k-1, a^*(k-1)). \tag{9}$$

The integer constraint on k makes a general analysis of this game tedious, explaining the widespread reliance on parametric examples in the literature. In order to overcome this problem, we treat the participation level k as a continuous variable.[17]

Formally, when there is a continuum of countries that simultaneously decide whether to join a coalition or not, the above conditions of external and internal stability can be written as follows:

$$\Pi_n(k, a^*(k)) \geq \lim_{l \to 0^+} \Pi_s(k+l, a^*(k+l)), \text{ and } \Pi_s(k, a^*(k)) \geq \lim_{l \to 0^+} \Pi_n(k-l, a^*(k-l)). \tag{10}$$

These conditions imply that an infinitesimally small country has no incentive to revise its participation decision, given the decisions of the other countries. Since the functions Π_s and Π_n are continuous, we have $\lim_{l \to 0^+} \Pi_s(k+l, a^*(k+l)) = \Pi_s(k, a^*(k))$ and $\lim_{l \to 0^+} \Pi_n(k-l, a^*(k-l)) = \Pi_n(k, a^*(k))$. Using this, it follows immediately that stable coalitions can not only be characterized by conditions (10) of external and internal stability, but equivalently by condition (11) below.[18]

Definition 1. *Consider continuous participation decisions, $k \in \mathbb{R}_+$. A coalition with $k \in (0, N)$ members is stable if*

$$\Pi_s(k, a^*(k)) = \Pi_n(k, a^*(k)). \tag{11}$$

The grand coalition, $k = N$, is stable if it satisfies the internal stability condition: $\Pi_s(N, a^*(N)) \geq \Pi_n(N, a^*(N))$.

Intuitively, because individual countries are infinitesimally small under the continuous membership approach, the coalition size remains k if a country unilaterally revises its participation decision. Therefore, no country has an incentive to do so if (11) is fulfilled, as this would not affect its payoff. Conversely, if (11) is violated, then a country with a lower payoff benefits from reversing its participation decision. For a grand coalition there are no non-signatories so that only the internal stability condition must be satisfied. Consequently, the grand coalition is also stable if the payoff of a coalition member is strictly larger than the payoff that it would obtain from leaving the coalition.

The subsequent proposition shows that the coalition size that follows from (11) is unique under mild conditions and has a further desirable property.

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[17] Martimort and Sand-Zantman (2013) assume a continuum of countries in their analysis of climate agreements. Haufler and Wooton (2010) analyze a location game, where (similar to our approach) the number of *firms* that decide to locate in each country is treated a continuous variable.

[18] It is not obvious for which values of k one can reasonably speak of a 'climate coalition' in the continuous approach. In line with the standard approach, this would be the case for $k \geq 2$. However, for the remaining analysis it is more convenient to adopt a broader perspective and refer to all $k > 0$ as a coalition. This is a choice of exposition, not of substance. All results remain valid if one restricts coalitions to, e.g., $k \geq 2$.

Proposition 1. *Consider a participation level $k^* \in (0, N)$ that satisfies* (11)*. If*

$$1 + \mu N - \frac{c'(a)c'''(a)}{(c''(a))^2} \geq 0, \tag{12}$$

then k^* is the unique interior solution of the continuous membership game, and at this solution

$$\tfrac{d}{dk}\left[\Pi_s(k, a^*(k)) - \Pi_n(k, a^*(k))\right] < 0. \tag{13}$$

Condition (12) is satisfied when $c'''(a) \leq 0$, or when $c'''(a) > 0$ but the third-order effect is not too strong. Moreover, for an isoelastic cost function

$$c(a) = a^z/z, \; z > 1, \tag{14}$$

the condition is always fulfilled since for this specification $c'c'''/(c'')^2 = (z-2)/(z-1) < 1$.[19] Note, that the isoelastic case includes the widely used quadratic specification (obtained for $z = 2$). Hence, the condition does not appear to be overly restrictive, and in the remainder we assume that it is satisfied.

Turning to the last statement in the proposition, suppose there exists an interior participation level $k \in (0, N)$ that satisfies (11), but $\Pi_s(k, a^*(k)) - \Pi_n(k, a^*(k))$ is *increasing* at this k, thus violating (13). Although k would still be an equilibrium outcome under the continuous membership approach, a deviation by an arbitrarily small but strictly *positive* mass of non-signatories would be profitable as this would lead to $\Pi_s(\cdot) > \Pi_n(\cdot)$. Condition (13) assures that such knife-edge cases do not arise in our model. Furthermore, the condition also has an intuitive interpretation. Namely, the difference of the payoffs as a coalition outsider, Π_n, and a coalition member, Π_s, reflects the free-rider incentives, and one would expect that these are *increasing* in the coalition size. Hence, the last result in Proposition 1 confirms that this is indeed the case in our model.

The next proposition shows that the coalition size that results from the continuous membership game provides a conservative estimate of the size that would obtain if the standard integer constraint were added to the problem.

Proposition 2. *Denote by $I(k)$ the largest integer smaller than or equal to k. Let k^* be the unique solution of the membership game with continuous participation decisions. Any integer k' that solves the internal and external stability conditions* (9) *is at least as large as $I(k^*)$.*

Intuitively, under the discrete approach, a deviation by a country at the participation stage leads to a non-marginal change in the size and, therefore, abatement of a coalition. This makes it more costly to leave a coalition, because the remaining signatories then reduce their abatement efforts. Our continuous membership approach ignores this effect, which explains why it (weakly) underestimates the coalition size.

Without BCA the payoff of a non-signatory would *always* be larger than the payoff of a coalition member because non-signatories share the same benefits of abatement but incur lower costs. Thus, according to Definition 1 the unique equilibrium outcome with continuous participation would be $A^* = k^* = 0$. BCA changes this picture significantly, and allows for higher participation in our model. In particular, the grand coalition is

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[19] The parameter z is the constant elasticity of the cost function, and $z > 1$ assures that $c(\cdot)$ is convex.

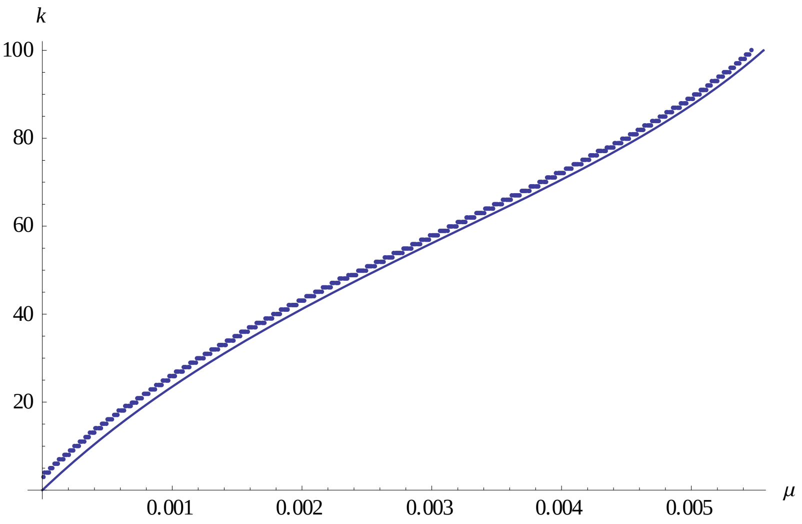

Figure 2: Effects of BCA on coalition size; solid curve: equilibrium participation under the continuous membership approach; 'step function': participation under the standard conditions of external and internal stability with discrete membership

stable if $\Pi_s(N, a^*(N)) \geq \Pi_n(N, a^*(N))$. Substituting from (6) and (7), thereby using (1), the condition becomes

$$(N\mu - 1)c(a^*(N)) + N\mu c'(a^*(N))(\bar{E} - a^*(N)) \geq 0. \tag{15}$$

Notice that $a^*(N)$ is independent of μ, because BCA plays no role when all countries cooperate (see (8)). The left-hand side of (15) is, thus, increasing in μ. Moreover, the first (negative) term converges towards 0 as μ converges to its upper limit, $1/N$. Since the second term is strictly positive, we obtain the following result.

Proposition 3. *There exists a $\tilde{\mu} \in (0, 1/N)$ such that the grand coalition obtains with BCA if and only if $\mu \geq \tilde{\mu}$.*

The solid line in Figure 2 depicts k^* (for continuous participation decisions) as a function of μ for the following specification: $h = 1, N = 100, b = 1, c(a) = 0.5a^2$, and $\bar{E} = 140$.[20] It shows (for this specification) that already low export shares are sufficient to trigger coalitions that are substantially larger than in the standard model. The grand coalition obtains once μ has reached a level that is slightly larger than half of its maximum value, $1/N = 0.01$.

In addition, observe that whenever the grand coalition is an equilibrium in the model with continuous participation decisions, then it is also an equilibrium according to the 'standard' stability condition (9) (this follows immediately from $I(N) = N$ and Proposition 2). The 'step function' in Figure 2 depicts the equilibrium participation level for the standard integer approach, i.e. based on conditions (9). The figure does not only confirm the continuous approach as being more conservative (Proposition 2), but also shows that both approaches do actually lead to quite similar results.[21]

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[20] Equilibrium abatement in the grand coalition is $a^*(N) = 100$. Hence $\bar{E}$ has been chosen such that emissions are reduced by roughly 70% in the grand coalition.

[21] Without trade and BCA, i.e. for $\mu = 0$, our model predicts $k^* = 3$ as the unique solution for the

Admittedly, Proposition 3 has been obtained from restrictive assumptions about trade patterns and the assumption that non-signatories do not implement climate policies. However, the following considerations suggest that dropping this assumption and using a more detailed trade model would still lead to the result that the grand coalition obtains with BCA if export shares are sufficiently large. Specifically, the grand coalition is an equilibrium outcome if no individual signatory has an incentive to leave it. If a country dropped out, its complete exports would still go to signatories and – with BCA – continue to be subject to the permit price in the coalition. Moreover, this non-signatory would now have to pay BCA-tariffs to the coalition members. Roughly speaking, this is the cost of leaving the coalition, which must be weighed against the benefit that production of polluting goods for the domestic market is no longer taxed, or taxed at a lower rate if Assumption 1 is dropped. Obviously, when countries' export shares are larger, the first effect is more costly and the second less beneficial. Intuitively, these effects should not hinge on the specifics of the trade model. The only critical feature is that under BCA – which makes production for exports to signatories less attractive – export shares of non-signatories do not drop too much. This mainly depends on the price elasticities of demand for domestic and foreign products. Our model skips this complication by assuming export shares to be constant (with BCA), respectively by assuming inelastic demands in the formalized trade model.

3 Climate cooperation with endogenous R&D

The climate cooperation game with BCA that was introduced in the previous section is now extended by assuming that countries can invest in low-carbon technologies in order to reduce their abatement costs. Whereas in the 'standard model' without trade the coalition size would always be $k^* = 3$ (assuming linear benefits and quadratic costs of abatement), in our model BCA allows for significantly larger coalition sizes. This leads to a non-trivial relation between countries' R&D efforts and the endogenous coalition size. Following Buchholz and Konrad (1994) as well as Beccherle and Tirole (2011), we assume that there is an *exogenous delay* in countries' efforts to cooperate on emission mitigation. Hence we add a new stage 0 to our climate cooperation model where countries determine their R&D efforts. For most parts of this section, it does not matter whether countries do so cooperatively or non-cooperatively because the results depend only on the aggregate R&D level.

Let $r_i \geq 0$ be country i's R&D effort. It is associated with a cost $f(r_i)$ that satisfies $f(r_i) > 0$, $f'(r_i) > 0$, $f''(r_i) > 0$ for all $r_i > 0$, as well as $f(0) = f'(0) = 0$, and $f''(0) \geq 0$. R&D efforts reduce the abatement cost parameter h. We assume that R&D is – like abatement – a pure public good so that h is now a function of the aggregate R&D level, denoted $R \equiv \sum_i^N r_i$. This reflects that technological knowledge can only partially be appropriated by those who invest in it, due to knowledge spillovers. A number of studies suggest that these are significant (e.g. Coe et al., 2009, Lee, 2003). The assumption that R&D is a *pure* public good highlights the problem of knowledge spillovers, and may be a reasonable approximation especially when the time span under consideration is long.

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integer approach. By contrast, in the standard model (e.g., Barrett, 1994) also $k^* = 2$ is an equilibrium. This difference is due to our assumption that non-signatories set $p_n = 0$ (Assumption 1). Intuitively, if non-signatories are restricted to abate less than would be optimal for them, it becomes more attractive to join the coalition. We relax Assumption 1 in Section 4.

Moreover, we assume a multiplicative specification of abatement costs, $c(a_i)h(R)$, where $h(R) > 0$, $h'(R) < 0$ and $h''(R) > 0$ for all $R \geq 0$, and $\lim_{R\to\infty} h(R) = 0$.[22] This has some nice properties which we exploit in the following analysis.

3.1 Effects of R&D investments on coalition game

The assumption that R&D is a pure public good assures that all countries are identical when they enter the coalition game as analyzed in Section 2.[23] Therefore, we assume that each country expects to face the same probability of becoming a coalition member (see, e.g., Barrett (2006), Hong and Karp (2012)). Accordingly, at the R&D stage the expected payoff per country is $\pi(R) \equiv \frac{k}{N}\Pi_s + \frac{N-k}{N}\Pi_n - f(r_i)$. Moreover, since countries are ex-ante identical, they will choose identical R&D efforts so that $r_i = R/N$. Using (6) and (7) this yields

$$\pi(R) = bA^*(R) - \frac{k^*(R)}{N}c(a^*(R))h(R) - f(R/N), \tag{16}$$

where $A^*(R) \equiv A^*(R, k^*(R))$ is total abatement (as function of R) when participation $k^*(R)$ and the abatement target $a^*(R) \equiv a^*(R, k^*(R))$ are determined as the equilibrium outcome of the coalition game (stages 1 and 2), given R.[24] Notice that transfers from non-signatories to signatories dropped out as ex-ante *expected* transfers are zero for each country. We obtain the following results for variations in the aggregate R&D effort, R.

Proposition 4. *For interior solutions at the participation stage, the abatement target a^* is independent of the R&D level R, and the coalition size $k^*(R)$ is decreasing in R. Therefore, higher R&D investments lead to less overall abatement, $A^* = k^*(R)a^*$. Furthermore, let ε denote the elasticity of the cost function $c(\cdot)$. If it satisfies*

$$\varepsilon \geq \frac{k}{N[1-\mu(N-k)]}\left(2 - \frac{\mu k}{1-\mu(N-k)}\right), \tag{17}$$

then each country's expected payoff, $\pi(R)$, is decreasing in R.

These results are fairly robust insofar as they have been obtained without imposing any further restrictions on the functions $h(\cdot)$ and $f(\cdot)$. Only the last result concerning welfare effects comes with the caveat of a sufficiently large elasticity of the cost function $c(\cdot)$. Specifically, we have $k/N[1-\mu(N-k)] \leq 1$ so that the right-hand side of (17) is strictly smaller than 2. Hence a sufficient condition is $\varepsilon \geq 2$, which includes the standard case of a quadratic cost function. Moreover, as k converges towards 0, the right-hand side of (17) also does so. The condition may, therefore, be satisfied also for substantially lower elasticities. In addition, (17) is itself only a sufficient condition because it neglects R&D costs (see the proof of Proposition 4). Since these are positive, the negative welfare effect of R obtains even for elasticities that violate (17). In conclusion, the caveat appears to be fairly weak, and for the remainder of the paper we assume that (17) is fulfilled.

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[22] See, e.g., Montero (2002) for a similar multiplicative specification.

[23] This occurs even if they choose different r_i, which would not be the case if R&D had private good properties. In this case one would have to check whether changing an individual r_i constitutes a profitable deviation even when all other countries undertake equal R&D investments. This requires to consider situations with non-identical abatement cost functions, which would complicate the analysis substantially.

[24] We use the same notation as in the previous section, but add the new argument R to the functions $A(\cdot)$ and $a(\cdot)$ in order to capture the dependency of h from R.

Intuitively, one would expect that the public good nature of R&D, which reduces the abatement cost of *all* countries, should trigger more abatement. Proposition 4 shows that this is not the case if one accounts for the strategic considerations that underlie the formation of a climate coalition. In particular, from Definition 1 coalitional stability requires that $\Pi_s(\cdot) - \Pi_n(\cdot) = 0$ or, after substitution from (6) and (7),

$$\mu N \left[\bar{E} - a^*\right] c'(a^*)h(R) - (1 - \mu N)c(a^*)h(R) = 0. \tag{18}$$

The first term represents the advantage of being a signatory because these countries receive transfer payments that non-signatories have to pay (recall that $p = c'h$). The second term represents the disadvantage because signatories have to abate more than non-signatories. In equilibrium, these two effects have to be balanced. The R&D term, $h(R)$, enters this expression in a multiplicative fashion and can be cancelled. Therefore, (18) implicitly determines the equilibrium abatement target a^* as a function of the exogenous parameters μ, N, and $\bar{E}$, while it is independent of R (first result in Proposition 4).

Nevertheless, higher R&D investments reduce marginal abatement costs, which would induce signatories to choose a higher abatement target a^* if the coalition size k were fixed (see (8)). However, this benefits non-signatories more than signatories because they realize the same benefits of abatement but incur a smaller share of the costs. This makes free-riding more attractive and participation declines for higher R&D levels (second result in Proposition 4). More formally, with a higher abatement target the coalitional stability condition (18) would no longer be satisfied. Since $a^*(R, k^*(R))$ is increasing in k^* from the first-order condition (8) for abatement, it follows that k^* has to fall in R.

Turning to the associated welfare effects, there is a trade-off. On the positive side, a higher R&D level reduces abatement costs for any given level of abatement. On the negative side, there are welfare losses due to the lower level of overall abatement, and R&D is costly. The result shows that the negative effects dominate for reasonable specifications of the abatement cost function.

3.2 Interior and boundary solutions of R&D

From Proposition 4, a country's welfare decreases in aggregate R&D as long as $k < N$. Since R&D is a pure public good (by assumption), welfare must also decrease in *individual* R&D efforts, r_i. It follows immediately that for any $k < N$ countries have an incentive to lower their R&D efforts until $R^* = 0$, irrespective of whether these are determined cooperatively or non-cooperatively. Such an equilibrium with $k^* < N$ and $R^* = 0$ is depicted in the lower graph of Figure 3.

From the discussion of Proposition 4, this result is driven by the effect that reducing R raises the coalition size k. Accordingly, it does no longer apply if the grand coalition $k^* = N$ is realized before R has been reduced to zero. Suppose that this is the case, and denote by R_0 the highest R&D level for which the grand coalition obtains in the equilibrium of the climate cooperation game. Formally, R_0 and $a^*(R_0)$ are implicitly determined from evaluating the equilibrium conditions at the participation and abatement stage (equations (18) and (8)) at $k = N$.[25] In Figure 3, it corresponds to the kink in the upper graph.

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[25] Recall that (18) implicitly determines the equilibrium abatement target independently of R. For this value of a, (8) may not have a (non-negative) solution for $h(R)$. Specifically, for $h(0)$ sufficiently small one gets $bN > c'(a)h(0)$, and $h(\cdot)$ is decreasing in R. Then we are in the scenario of the lower graph in

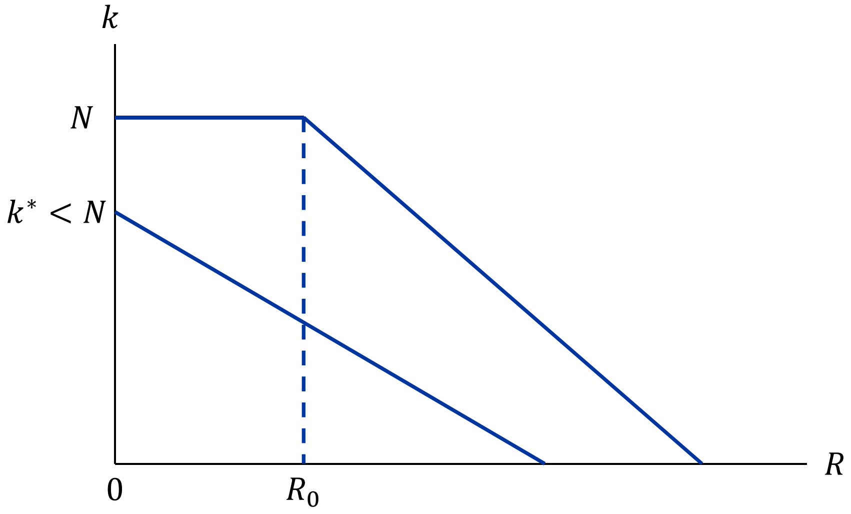

Figure 3: Endogenous coalition size k as a function of R&D investments R; lower graph: an interior participation level $k < N$ is reached when $R = 0$; upper graph: a grand coalition forms when $0 \leq R \leq R_0$.

However, if R&D is sufficiently costly, then it may be beneficial to reduce R below the level R_0. This leads to a grand coalition with $\Pi_s(\cdot) > \Pi_n(\cdot)$ (see Definition 1). Nevertheless, even in such a situation countries always undertake *some* investments in R&D due to our assumption $f'(0) = 0$, i.e. the first marginal unit of R&D is costless.

To determine the equilibrium R&D level for this case, consider a 'modified game' in which participation is *exogenously* fixed at $k = N$. Denote the equilibrium R&D effort in this modified game by R_N. Since strategic effects related to endogenous changes in participation do not arise in this case, R_N generally differs from R_0. If $R_N \geq R_0$, then in the 'full game' the equilibrium R&D effort is R_0, because a higher R&D effort would reduce participation (by definition of R_0) and welfare (by Proposition 4). This implies a boundary solution $R^* = R_0$. However, if $R_N < R_0$, then the equilibrium R&D effort in the full game is equal to R_N, as countries benefit from reducing their R&D effort below R_0. This leads to a solution $R^* < R_0$, which is interior in the sense that R could be raised without compromising the grand coalition.

In contrast to R_0, the value of R_N depends on whether countries determine their R&D efforts in stage 0 cooperatively or non-cooperatively. Denote the value of R_N in these two cases by R_N^c and R_N^{nc}, respectively. To determine R_N, note first that the abatement target a follows again from (8). The reason is that when signatories choose their abatement target in stage 2, it is irrelevant whether participation was determined as part of the equilibrium outcome of the full game (in stage 1), or whether it is exogenously fixed (as in the modified game that we are considering here). At $k = N$ this yields the first-order condition

$$bN - c'(a)h(R_N) = 0. \tag{19}$$

Turning to R&D efforts in this modified game, first suppose that these are determined

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Figure 3, for which $R^* = 0$ and $k^* < N$. The Inada-type condition $h(0) = \infty$ would assure that there is an interior solution for R_0. However, the assumption that marginal abatement costs are infinitely large without R&D investments is not very convincing.

non-cooperatively, which is probably the more relevant case. Then for an interior solution, R_N^{nc} follows from maximizing a country's expected payoff as given by (16) at $k^* = N$ with respect to r_i. The resulting first-order condition is (using (19)):[26]

$$-c(a)h'(R_N^{nc}) = f'(R_N^{nc}/N). \tag{20}$$

Alternatively, if R&D efforts are determined *cooperatively*, r_i maximizes the sum of expected payoffs over all countries, yielding the first-order condition for R_N^c (using (19) and noting that the last term in (16) represents $f(r_i)$):

$$-Nc(a)h'(R_N^c) = f'(R_N^c/N). \tag{21}$$

Accordingly, $\{a^*(R_N^{nc}), R_N^{nc}\}$ follow from (19) and (20), and $\{a^*(R_N^c), R_N^c\}$ from (19) and (21). The latter system also characterizes the R&D effort and abatement in the first-best outcome, since both externalities are fully internalized. Obviously, R&D and, therefore, abatement are larger than in the non-cooperative case.[27] Nevertheless, if R&D efforts are determined non-cooperatively ($R_N = R_N^{nc}$), then free-riding at the R&D stage of the full game only occurs if $R_N^{nc} < R_0$. Otherwise (i.e., when $R_N^{nc} \geq R_0$), the equilibrium R&D level is R_0, independent of whether countries choose R&D cooperatively or non-cooperatively.

Finally, note that the above first-order conditions may not always deliver a (unique) interior solution for R_N^{nc} and R_N^c because the second-order conditions may not be satisfied for the general model specification. We discuss this problem at the end of Appendix A (for the non-cooperative case). There, it is also shown that when $c(\cdot)$ is isoelastic with $z \geq 2$ and $h(R) = 1/R$, then the second-order condition for R_N^{nc} to be a maximum is always fulfilled. We summarize our findings in the following proposition.

Proposition 5. *If there exists an* $R_0 \geq 0$ *that solves* (18) *and* (8) *at* $k = N$*, then the grand coalition forms, and the equilibrium R&D level is* $R^* = \min\{R_0, R_N\}$*, where* $R_0 \geq 0$ *and* $R_N > 0$*. Otherwise, countries do not invest in R&D (*$R^* = 0$*), and a smaller coalition forms (*$k^* < N$*). Furthermore, the critical value* R_0 *is increasing in* μ*.*

Recall that a higher μ implies that BCA has a greater impact. Hence the last statement suggests that BCA has not only a positive effect on the coalition size (Proposition 3), but also on R&D efforts. Specifically, this happens if $R_0 < R_N$ so that the equilibrium R&D level is $R^* = R_0$.

4 R&D with climate policies by non-signatories

The preceding analysis was based on Assumption 1 that non-signatories do not implement own emission reduction policies. However, if $c'(0) = 0$ this imposes a sub-optimal policy upon non-signatories so that it becomes relatively more appealing to be a signatory. Hence, dropping Assumption 1 leads to smaller coalitions. However, this does not change the central effects of BCA, that still make coalition membership more attractive. As

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[26] Notice that with $k = N$ fixed, $a^*(R)$ depends on R – in contrast to the result of Proposition 4 that is valid only for an interior solution at the participation stage.

[27] Notice that in both cases of cooperative and non-cooperative R&D choices, R_N is independent of $\bar{E}$ and μ, in contrast to R_0. The reason is that R_N is the equilibrium R&D level for $k = N$, and when the grand coalition forms there is no BCA so that the parameters $\bar{E}$ and μ are irrelevant.

we discussed at the end of Section 2, also a grand coalition can still obtain, but when Assumption 1 is relaxed this requires larger export shares. E.g., for the model specification and parameter values that are underlying Figure 2, the critical export share $\tilde{\mu}$ beyond which the grand coalition is obtained rises from about 0.006 to 0.007 if Assumption 1 is dropped. In the following, we thus focus on the implications of Assumption 1 for the relation between R&D efforts and welfare.

When analyzing the case where also non-signatories implement climate policies, for consistency we apply Assumption 2 to them as well. Hence, we assume that also non-signatories do not strategically 'manipulate' their climate policies in order to generate additional revenues via BCA-tariffs. In particular, this implies that a non-signatory cannot obtain BCA-transfers from raising its carbon price unilaterally above the level of the other non-signatories. We motivated this assumption with reference to WTO rules. By contrast, there is no reason why a non-signatory should not take into account that a higher carbon price *reduces* its transfers to signatories. Hence, we allow for this strategic BCA-effect.[28] Indexing an individual non-signatory country by j then yields the following welfare function (gross of R&D costs):

$$\Pi_j = bA - k\mu c(a_s)h - (N-k-1)\mu c(a_n)h - [1-(N-1)\mu]c(a_j)h - k\mu(p_s - p_j)(\bar{E} - a_s), \quad (22)$$

where a_n is the abatement target of the $N-k-1$ other non-signatories. Intuitively, $bA = b[ka_s + (N-k-1)a_n + a_j]$ are the benefits of abatement, $k\mu c(a_s)h$ and $(N-k-1)\mu c(a_n)h$ are abatement costs for exports of country j to signatories and non-signatories, respectively, $[1-(N-1)\mu]c(a_j)h$ are abatement costs for domestic sales, and $k\mu(p_s - p_j)(\bar{E} - a_s)$ are net BCA-transfers to the k signatories. Transfers between country j and other non-signatories were omitted in (22), because they are equal to zero in an equilibrium that is symmetric across non-signatories (see below), and because Assumption 2 rules out a strategic manipulation of p_j with the goal to obtain such transfers. Using $p_j = c'(a_j)h$ in (22), we obtain the following first-order condition for a non-signatory's choice of a_j:

$$b - [1-(N-1)\mu]c'(a_j)h + k\mu c''(a_j)h(\bar{E} - a_s) = 0. \quad (23)$$

Thus, when choosing its abatement target, a non-signatory accounts for the environmental benefits (first term) and the additional abatement costs for domestic sales (second term). In addition, it takes into account that a higher target a_j, implemented by a higher carbon price p_j, reduces its transfer payments to signatories (third term). Moreover, it follows from (23) that all non-signatories choose the same abatement target.

Apart from the extension that also non-signatories set an abatement target, the model and the solution procedure are the same as discussed in Sections 2 and 3.[29] Nevertheless, the additional complexity that arises if one endogenizes the abatement target of the non-signatories makes the model inaccessible to a *non-parametric* analysis. Therefore, we

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[28] We rule out the possibility that non-signatories could charge a different tax rate to firms depending on whether they are exporting their goods to signatories or non-signatories. This would allow them to avoid transfer payments to the signatories. To justify this, one might assume that all countries have to apply the same tax rate to all firms. Tax reductions for firms located in signatories that are exporting to non-signatories may, then, be implemented as 'tax rebates' that are allowed under BCA, while non-signatories cannot grant such rebates to firms that supply the domestic market. Hence, in order to reduce their BCA-transfers to the signatories, they need to charge a higher carbon price to all firms.

[29] The details are, thus, omitted here for the sake of brevity, but can be obtained from the authors upon request.

resort to a simple numerical analysis, based on a quadratic specification of abatement costs: $c(a_i) \equiv a_i^2/2$.

Figure 4 shows welfare Π (gross of R&D costs) per country as a function of R&D investments, R.[30] All curves are plotted for values of R that yield interior participation levels, $k^*(R)$, between $k^* = N$ (left part of the figure) and $k^* = 1$ (right part of the figure).[31] The solid curve represents the 'extended model' with $p_n > 0$. The declining dotted curve shows gross welfare in the 'reduced model' with $p_n = 0$, as analyzed in Sections 2 and 3. Finally, the increasing dotted line illustrates the fully non-cooperative benchmark case where $k = 0$ is exogenously fixed, but $p_n > 0$.

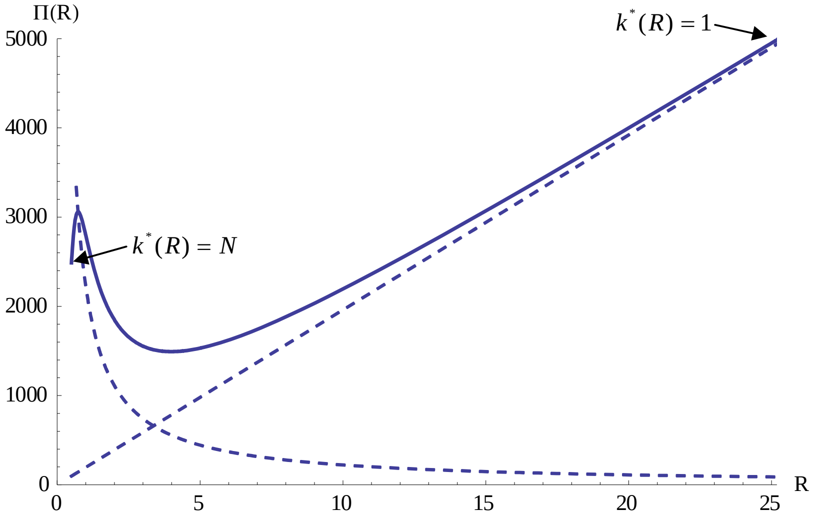

Figure 4: Gross welfare per country as function of R; solid curve: extended model with $p_n > 0$; declining dotted curve: reduced model with $p_n = 0$; increasing dotted line: non-cooperative benchmark with $k \equiv 0$

First consider the right part of the figure. When R becomes large, participation in the extended model becomes small (in line with Proposition 4) and approaches the level in the fully non-cooperative benchmark. Nevertheless, significant abatement occurs because it becomes cheaper due to better technologies. This explains why welfare in the extended model and in the non-cooperative benchmark converge when R becomes large, and why welfare increases in R for these two cases.[32] By contrast, in the reduced model non-signatories do not abate by assumption. Therefore, the lower participation that follows from a higher R reduces welfare (see Proposition 4).

Next, we turn to the left part of the figure. As R becomes small, participation and, therefore, welfare increases in the reduced model until the grand coalition obtains, i.e.,

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[30] Figure 4 is based on the following parameter values: $b = 1$, $\bar{E} = 100$, $N = 100$, and $\mu = 0.5 \cdot 1/N$. Hence, the export share of polluting goods per country, $\mu(N-1)$, is roughly 50%. We varied these parameter values over a wide range to check the robustness of our qualitative findings. For empirical data on export shares, see, e.g., http://data.worldbank.org/indicator/NE.EXP.GNFS.ZS/countries.

[31] In the case with $p_n > 0$, the range for an interior solution at the participation stage is $k \in (1, N)$, rather than $k \in (0, N)$. This is due to the fact that for $k = 1$, the single signatory behaves in the same way as each of the non-signatories, while for $k < 1$ a signatory would implement a lower emissions price than the non-signatories.

[32] Recall, however, that Figure 4 depicts *gross* welfare. When R&D costs, $f(r_i)$, are sufficiently large, net welfare, $\pi(R) = \Pi(R) - f(r_i)$, may still be decreasing in $R = Nr_i$.

until $k^*(R) = N$. In principle, this also happens in the extended model. However, the remaining non-signatories pay substantial BCA-transfers to signatories because this group has become large. In the extended model, each non-signatory responds to this by raising its carbon price. Formally, this effect is represented by the last term in (22), which is large if k is large. Given that this adjustment substantially reduces BCA transfer payments, welfare of a remaining non-signatory improves, making it less attractive to become a signatory. In the reduced model, this adjustment is excluded by fixing $p_n = 0$. This makes it less attractive to remain a non-signatory so that the coalition size in the reduced model is significantly larger than in the extended model when R is small. In Figure 4 this has two implications. First, welfare in the reduced model starts to exceed welfare in the extended model as R becomes small. And second, the grand coalition is obtained for (slightly) higher values of R in the reduced model.

Moreover, recall that the negative effect of R on welfare in Proposition 4 was caused by the following 'crowding out effect': A higher R makes abatement less costly so that a coalition *of given size* abates more, but this 'crowds out' the incentives to become a coalition member in the first place. Hence the coalition size falls. In the preceding paragraph we have explained that this effect is less strong in the extended model, i.e. the coalition size does not fall so strongly as R is raised. Therefore, the lower abatement costs that follow from a higher R may dominate the crowding out effect. This explains why in the extended model the curve $\Pi(R)$ first *increases* in R, before it starts to decline again due to the crowding-out effect.

Overall, Figure 4 suggests that two types of outcomes may occur in equilibrium. For high R&D costs, an equilibrium is attained in which R is small while equilibrium participation is high. This mirrors our results from Section 3. However, unlike in the case where $p_n = 0$, a grand coalition is generally not reached.[33] This is due to the presence of the local maximum in the welfare function at low values of R. Nevertheless, the central result of Section 3 is preserved when we drop Assumption 1: despite the formation of a large coalition, the realized welfare gains are limited due to significant underinvestments in R&D. Alternatively, an equilibrium can be attained with higher investments in R&D, but low participation. The final outcome then resembles the outcome in the fully non-cooperative benchmark case with $k = 0$. However, this type of equilibrium can only exist if the R&D cost function, $f(r_i)$, is sufficiently flat so that also *net* welfare per country is U-shaped.[34]

In conclusion, when non-signatories implement climate policies, the free-rider incentive can manifest itself *either* in the R&D-dimension with significant underinvestments in low-carbon technologies but high participation (similarly as in Section 3), *or* in the participation dimension (similarly as in Barrett, 1994), in which case the underinvestment problem is less severe.

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[33] This depends on the exact shape of the function $f(\cdot)$, that is not specified here.

[34] If both equilibria coexist, then equilibrium selection is a matter of coordination. In the context of climate cooperation, a coordination game can also arise when there is a threshold for emissions where discontinuous damages are incurred, as shown in Barrett (2013). This stabilizes a cooperative outcome because a unilateral deviation by a country towards higher emissions can trigger the 'catastrophe'. In our model, when two equilibria exist, the coordination game is played at the R&D stage. Either countries coordinate to strategically underinvest, which leads to an equilibrium with high participation, or countries coordinate on larger investments, which leads to an outcome with low participation but more substantial abatement by the non-signatories.

5 Concluding remarks

In order to tackle the issue of climate change, countries must undertake costly actions to reduce their greenhouse gas emissions. They must also invest in low-carbon technologies in order to achieve their abatement targets at a reasonable cost. In the light of strong knowledge spillovers, climate change mitigation is thus a global ‘double public goods problem’. If a global agreement that fixes countries’ abatement *and* R&D efforts is currently not feasible, then the question arises whether early action in the development of low-carbon technologies may pave the way towards a more effective outcome in the future.

Using a stylized cooperation model, we show that border carbon adjustments can be quite effective in addressing the participation problem and guiding countries into a climate coalition. By contrast, our results indicate that early unilateral investments in low-carbon technologies may not necessarily improve the outcome of a future climate agreement. In particular, while such investments reduce future abatement costs and trigger additional abatement efforts (for a fixed coalition size), they also aggravate the free-rider incentive, thereby undermining the potential welfare gains of a future climate agreement.

In our model, the crowding-out effect via reduced participation is often so strong that early technology investments are even harmful. Hence, anticipating membership decisions in a future climate coalition as well as its abatement effort, countries strategically underinvest in low-carbon technologies. This way, a future agreement may even reach full participation, but the welfare gains achieved by this grand coalition are limited due to underinvestment in R&D, which implies inefficiently high abatement costs and too little abatement.

This suggest that an effective international environmental agreement on climate change requires high participation, and must fix not only countries’ abatement efforts, but also R&D efforts. In our analysis, we did not consider the case where coalitions decide simultaneously about abatement and R&D. However, we conjecture that the free-rider incentive might be even more pronounced. Intuitively, more R&D triggers additional abatement by the coalition, and a higher abatement target makes further R&D efforts by the signatories profitable. Thus the two reinforce each other. By contrast, non-signatories would have little incentive to invest in either of the two public goods, but benefit from the signatories’ efforts. This raises the attractiveness of being a coalition outsider, aggravating free-rider incentives. We have seen that BCA may be helpful to address this problem, assuming that it is possible to resolve the political and implementation problems associated with it (which may be substantial). Furthermore, its effectiveness will depend on countries’ export shares being large enough. Especially in a globalized world economy, BCA may be effective in guiding countries into a future climate agreement.

Despite the negative effects of early efforts to bring down the costs of low-carbon technologies in our model, the results should not be interpreted as saying that these are *generally* counter-productive. Potentially important aspects of the problem such as altruism (some countries may sacrifice more than they can expect to gain from an agreement), or the possibility of a ‘technological breakthrough’ and increasing returns in the renewable energy sector are omitted. Hence policy implications should be treated with caution. Nevertheless, what our model does show is that early investments in technology do not *automatically* lead to a better outcome in future climate negotiations. Climate cooperation remains a challenge, and this challenge may become even bigger if low-carbon technologies are available at lower costs, due to a stronger free-rider incentive. Notwithstanding, one should also keep in mind that the *potential gains* of cooperation are larger when abatement costs are reduced. Hence, our results may challenge policy makers to try even harder to reach an agreement.

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Appendix A: Proofs

Proof of Lemma 1. For $k > 0$, implicit differentiation of (8) yields (after rearranging):

$$\frac{da^*}{dk} = \frac{b - \mu c'(a^*)h}{[1 - \mu(N-k)]c''(a^*)h}. \tag{24}$$

The denominator is positive because $1 > \mu(N-k)$ and $c''(a^*) > 0$ for any $a^* > 0$ by assumption. Moreover, using (8) to substitute for $c'(a^*)h$, the numerator becomes

$$b - \mu c'(a^*)h = \frac{b(1-\mu N)}{1-\mu(N-k)} > 0$$

since $\mu N < 1$ by assumption. □

Proof of Proposition 1. In order to prove uniqueness and to show that the stability condition (13) is satisfied, define $\Delta\Pi(k,a) \equiv \Pi_s(k,a) - \Pi_n(k,a)$. Substitution from (6) and (7), thereby using (1), yields at the equilibrium abatement target $a^*(k)$,

$$\Delta\Pi(k, a^*(k)) = c'(a^*(k))h\mu N \left[\bar{E} - a^*(k)\right] - (1-\mu N)c(a^*(k))h. \tag{25}$$

Differentiation w.r.t. k and again simplifying terms gives

$$\frac{d\Delta\Pi(k,a^*(k))}{dk} = \left[c''(a^*)\mu N(\bar{E}-a^*) - c'(a^*)\right] h\frac{da^*}{dk}. \tag{26}$$

From (8) and the curvature assumptions, $a^*(k) = 0$ at $k = 0$, and $a^*(k) > 0$ for all $k > 0$. Hence da^*/dk and – again using the curvature assumptions – the whole term (26) are non-negative at $k = 0$. Moreover, for $k > 0$, substituting for da^*/dk from (24) gives

$$\frac{d\Delta\Pi(k,a^*(k))}{dk} = \left(\mu N(\bar{E}-a^*) - \frac{c'(a^*)}{c''(a^*)}\right)\frac{b-\mu c'(a^*)h}{1-\mu(N-k)}. \tag{27}$$

The second term is always positive from the proof of Lemma 1. Moreover, $\mu N a + c'/c''$ increasing in a, which is equivalent to $1+\mu N-(c'c''')/(c'')^2 \geq 0$, is a sufficient condition for the first term to be decreasing in $a^*(k)$ and, therefore, in k (by Lemma 1). Accordingly, $d\Delta\Pi/dk$ is non-negative at $k = 0$ and can change its sign at most once thereafter (from positive to negative) if $\mu N a + c'/c''$ is (weakly) increasing in a. Hence, as $a^*(0) = 0$ and $\Delta\Pi(0,0) = 0$, there can be at most one solution $k > 0$ that satisfies $\Delta\Pi(k, a^*(k)) = 0$, and at this solution $d\Delta\Pi/dk < 0$, i.e. it satisfies (13). □

Proof of Proposition 2. Suppose to the contrary of the proposition that there exists an integer $k' < I(k^*)$ that satisfies inequalities (9), in particular the external stability condition (for ease of notation, we write $\Pi_i(k)$ for $\Pi_i(k, a^*(k))$)

$$\Pi_n(k') \geq \Pi_s(k'+1). \tag{28}$$

Recall that $d\Delta\Pi/dk$ is non-negative at $k = 0$ (see the proof of Proposition 1) and $\Delta\Pi(0) = 0$. If k^* is the unique solution to (11), then it also satisfies (13) (by Proposition 1). It follows that $\Pi_n(k) \leq \Pi_s(k)$ for all values of $k < k^*$.[35] Moreover, since $I(k^*)$ is the largest integer smaller than or equal to k^* and $k' < I(k^*)$, we have $k' < k'+1 \leq I(k^*) \leq k^* \leq N$. Therefore, $\Pi_n(k') \leq \Pi_s(k')$ and $\Pi_n(k'+1) \leq \Pi_s(k'+1)$. Finally, the overall surplus is clearly monotonic in k since this implies a larger internalization of the externality and BCA effects cancel out in the aggregate, i.e., $k'\Pi_s(k') + (N-k')\Pi_n(k') < (k'+1)\Pi_s(k'+1) + (N-(k'+1))\Pi_n(k'+1)$. Collecting the above yields

$$\begin{aligned} N\Pi_n(k') &\leq k'\Pi_s(k') + (N-k')\Pi_n(k') \\ &< (k'+1)\Pi_s(k'+1) + (N-(k'+1))\Pi_n(k'+1) \leq N\Pi_s(k'+1), \end{aligned}$$

a contradiction to (28). □

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[35] This is also the case for a grand coalition with $\Pi_n(N) < \Pi_s(N)$ since in this case there can be no k for which $\Pi_n(k) = \Pi_s(k)$ (because $\Delta\Pi(0) = 0$ and $\Delta\Pi(k)$ can change its sign at most once thereafter from positive to negative; see proof of Proposition 1).

Proof of Proposition 3. Follows from the arguments in the main text. □

Proof of Proposition 4. We only need to consider interior solutions at the participation stage. For these, recall that the equilibrium values $a^*(R, k^*(R))$ and $k^*(R)$ are defined by (11) and (8). Substituting from (6) and (7), they solve

$$bk(R) - [1 - \mu(N - k(R))]\, c'(a(R, k(R)))h(R) = 0 \tag{29}$$
$$(1 - \mu N)c(a(R, k(R))) - \mu N c'(a(R, k(R)))[\bar{E} - a(R, k(R))] = 0. \tag{30}$$

These conditions must hold for all values of R; hence we can differentiate them with respect to R. Doing so for (30) yields after rearranging

$$\left[c'(a^*) - \mu N c''(a^*)(\bar{E} - a^*)\right] \frac{da^*}{dR} = 0. \tag{31}$$

From Proposition 1, $\frac{d\Delta\Pi(k, a^*(k))}{dk} < 0$ at the equilibrium values a^* and k^*. From (26) this implies that the term in square brackets is positive. Hence $da^*(R, k^*(R))/dR = 0$. Using this when differentiating (29) with respect to R and rearranging yields

$$\frac{dk^*}{dR} = \frac{[1 - \mu(N - k^*)]c'(a^*)h'(R)}{b - \mu c'(a^*)h(R)}. \tag{32}$$

The numerator is negative by the curvature assumptions, and the denominator is positive by the proof of Lemma 1; hence $dk^*/dR < 0$.

Turning to the welfare result, differentiating expected payoffs gross of R&D costs, i.e. $\Pi(R) \equiv \pi(R) + f(R/N)$, yields (using (16), and suppressing asterisks * for ease of notation)

$$\begin{aligned} \frac{d\Pi(R)}{dR} &= k'(R)(ba - c(a)h(R)/N) - k(R)c(a)h'(R)/N \\ &= \frac{kh'(R)}{N(1 - \mu N)h(R)} \left[N(1 - \mu N + \mu k)ba - (2 - 2\mu N + \mu k)c(a)h(R)\right], \end{aligned}$$

where the second line follows from using (32) to replace $k'(R)$, and then (29) to replace $c'(a)$. Since $h'(R) < 0$ and $1 > \mu N$, it remains to show that the expression in square brackets is positive. Using (29) to replace $h(R)$, this yields the following condition:

$$\varepsilon \equiv \frac{ac'(a)}{c(a)} > \frac{k(2 - 2\mu N + \mu k)}{N(1 - \mu N + \mu k)^2}.$$

The right-hand side is positive so that the elasticity, ε, of the cost function $c(a)$ must be sufficiently large. Specifically, adding and subtracting μk in the numerator on the right-hand side, the expression becomes

$$\varepsilon > \frac{k}{N}\left(\frac{2(1 - \mu N + \mu k) - \mu k}{(1 - \mu N + \mu k)^2}\right) = \frac{k}{N[1 - \mu(N - k)]}\left(2 - \frac{\mu k}{1 - \mu N + \mu k}\right).$$

It follows that $d\Pi(R)/dR < 0$ if and only if this is satisfied. Moreover, in this case also net welfare $\pi(R)$ is decreasing in R because $f(r)$ is increasing in $r = R/N$. □

Proof of Proposition 5. Most results follow from the discussion in the main text (preceding the proposition), and using Proposition 4. However, it remains to show that $R_N > 0$ and that $R_0'(\mu) > 0$. Starting with the first, recall that at $k = N$, the first-order condition for abatement is (19). Since $c'(0) = 0$, it implies that $a > 0$. But with $a > 0$, the first-order conditions for non-cooperative and cooperative R&D choices, (20) respectively (21), cannot be fulfilled for $R_N = 0$, because $f'(0) = 0$ and $h'(0) < 0$ by assumption.

To prove $R_0'(\mu) > 0$, recall that R_0 follows from (18), as well as (8) evaluated at $k = N$. For interior solutions $R_0 > 0$, implicit differentiation of this system yields (after rearranging and again using (18) to simplify terms):

$$\frac{dR_0}{d\mu} = \frac{c(a^*)c''(a^*)h(R_0)}{\left[\mu N c''(a^*)(\bar{E} - a^*) - c'(a^*)\right] \mu c'(a^*)h'(R_0)}. \tag{33}$$

The term in square brackets in the denominator of (33) is negative from using (13) in Proposition 1 to evaluate the right-hand side of (26) in the corresponding proof. Using this and the curvature assumptions, it follows that $R_0'(\mu) > 0$. □

Discussion of the second-order condition for R_N^{nc}:
In the proof of Proposition 5 we have already shown that when $k = N$ is fixed, then countries choose positive R&D efforts (hence, $R_N^{nc} > 0$). However, the system (19) and (20) can have several solutions in the range $0 < R \leq R_0$. To see this, note that the second-order condition for optimal R&D investments follows from differentiating (20) with respect to r_i, and implicit differentiation of (19) to substitute for $a'(R)$. This yields:

$$\frac{(c'(a^*)h'(R))^2}{c''(a^*)h(R)} - c(a^*)h''(R) - f''(R/N) < 0. \tag{34}$$

This condition is not generally fulfilled, and there is an intuitive explanation for that. Namely, if countries invest more in R&D, then abatement costs fall for any given abatement target. However, also the optimal abatement target of the grand coalition rises. This gives scope for increasing returns to investments in R&D, which may lead to multiple local maxima of the function $\pi(R)|_{k=N}$. Nevertheless, we can state a condition under which such a case cannot arise. In particular, dropping $f''(\cdot)$ in (34), a sufficient (albeit not necessary) condition for the above second-order condition to be fulfilled is

$$\frac{c(a)c''(a)}{(c'(a))^2} \geq \frac{(h'(R))^2}{h(R)h''(R)}.$$

Because this condition is not very intuitive, let us consider the example of an isoelastic cost function (as specified in (14)) and $h(R) = 1/R$.[36] In this case, it is easy to verify that $c(a)c''(a)/(c'(a))^2 \geq 1/2$ when the elasticity of the cost function z is greater than or equal to 2, and $(h'(R))^2/h(R)h''(R) = 1/2$. Hence, for this example, the second-order condition for R_N to be a maximum is always fulfilled.

Appendix B

Formal description of the basic trade model

Each country is initially endowed with a non-polluting, tradeable numeraire good. This good can be consumed directly or converted into a variety of polluting goods. Each

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[36] These functional forms are also used to construct Figure 4 in the numerical analysis of Section 4.

country is specialized in the production of a specific polluting good.[37] Hence, the polluting goods produced by different countries are differentiated. Let x_{ij} be the quantity of the polluting good that is produced in country j and consumed in country i (x_{ii} is the quantity of the polluting good produced and consumed domestically in country i). We assume that the utility function U_i of the representative consumer in country i is quasi-linear and has the following form:

$$U_i = y_i + z \sum_{j \neq i} \min \left\{ \frac{\hat{f}}{(N-1)\hat{f} + \hat{d}}, x_{ij} \right\} + z \min \left\{ \frac{\hat{d}}{(N-1)\hat{f} + \hat{d}}, x_{ii} \right\} - b \sum_j E_j, \quad (35)$$

where y_i is consumption of the numeraire good, E_j are country j's emissions, and b is the marginal damage of emissions. Finally, z is the constant marginal utility of consuming each of the foreign goods as long as $x_{ij} \leq \frac{\hat{f}}{(N-1)\hat{f}+\hat{d}} \equiv f$, and the domestic good as long as $x_{ii} \leq \frac{\hat{d}}{(N-1)\hat{f}+\hat{d}} \equiv d$. Thus f and d are the maximum quantity of each foreign and the domestic good that the consumer in each country i wishes to consume. Moreover, a higher $\hat{f}$ implies a stronger preference for foreign goods, and a higher $\hat{d}$ a stronger preference for the domestic good.

The assumption of a constant marginal utility (up to the most preferred quantity) is borrowed from the 'Hotelling model' that is frequently used in industrial organization theory (see, e.g., Tirole, 1988, p. 97).[38] We assume $z > 1$ so that the consumer prefers the polluting goods over the numeraire good for all $x_{ij} < f$ and $x_{ii} < d$. Finally, note that the fractions in the two min-expressions consist of exogenous parameters only. They have been chosen such that in equilibrium a country's total consumption of foreign goods, $(N-1)f$, and of the domestic good, d, is normalized to 1 (see below).

For parsimony, we assume that in each country i there are N firms that produce the domestic polluting good. $N-1$ of them are completely specialized on exactly one of the $N-1$ export markets, and the remaining firm exclusively serves the domestic market. Hence, each of the N firms located in country i is a monopolistic supplier of country i's domestic good in the market that it serves. Later on, this setup will allow us a very straightforward analysis of production and relocation decisions if countries choose different emission prices. Nevertheless, for the moment we take the locations of firms as given. Normalizing the price of the numeraire good to 1, the budget constraint of the representative consumer in country i is, thus

$$y_i + \sum_j P_{ij} x_{ij} \leq \bar{Y}_i + \sum_j \pi_{ji} + T_i, \quad (36)$$

where P_{ij} is the price of the polluting good produced in country j and sold in country i, $\bar{Y}_i$ is country i's endowment of the numeraire good, π_{ji} is the profit of the firm located in country i that sells its output in country j, and T_i are revenues of country i from taxing of emissions (see below). We assume that the representative consumer has sufficient initial wealth $\bar{Y}_i$ such that he can always afford f units of each of the $N-1$ foreign goods and d units of the domestic good. Maximization of (35) subject to (36) then yields fixed

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[37] Alternatively, we could assume that each country offers different varieties of a differentiated good (see, e.g., Feenstra, 2003, chapter 5). The assumption that each country provides only one type of polluting good simplifies the exposition because we do not need to introduce an index for the varieties. What is crucial for our approach is merely the assumption of inelastic demands.

[38] The resulting type of demand function is also known as 'unit demand'.

consumption patterns $x_{ij} = f$ and $x_{ii} = d$ that are identical across countries. Moreover, overall consumption of polluting goods in each country is $(N-1)f + d = 1$.

Turning to production, suppose that one unit of a polluting good yields $\bar{E}$ units of pollution when firms do not abate. Let q_{ij} be the output of the monopolist in country j who sells in country i, and let a_{ij} be the *abatement intensity* (= abatement of emissions per unit of output) of this firm. Furthermore, let $C_{ij}(q_{ij})$ be the production cost function of this firm (i.e., the amount of numeraire good needed to generate q_{ij} units of the polluting good), and $q_{ij}c(a_{ij})h$ its abatement cost.[39] Under BCA, all firms that sell in country i face the emission price $p_i \geq 0$ that prevails in this country. For the firm located in country j that sells its output in country i, this yields profits of

$$\pi_{ij} = P_{ij}q_{ij} - C_{ij}(q_{ij}) - q_{ij}c(a_{ij})h - p_i(\bar{E} - a_{ij})q_{ij}, \tag{37}$$

including the case where $j = i$ (π_{ii} is the profit of the firm in the polluting sector of country i that sells to the domestic consumer).

A firm located in country j that sells in country i thus chooses its abatement intensity according to the first-order condition $p_i = c'(a_{ij})h$. Under BCA all firms that sell their output in country i face the same emission price p_i and, therefore, choose the same abatement intensity, denoted by a_i in the remaining. Observe that this holds independently of whether the firm is located in country j, or relocates to any of the other countries. Hence, when a functioning BCA-system is established, then no firm has an incentive to relocate, independently of the carbon prices established by the different countries. By contrast, without BCA, the whole output in a country i would be subject to the carbon price in this country. Thus, whenever there exists some other country j that charges a lower carbon price than country i, then all polluting firms in country i would relocate (provided that relocation costs are not too high).

It remains to specify output prices and quantities. We assume that the marginal utility z of consuming each of the polluting goods exceeds their marginal production costs plus any marginal emission costs that may arise when countries implement carbon prices; i.e., $z > C'_{ij}(q_{ij}) + c(a_i)h + p_i(\bar{E} - a_i)$ for all i, j, $q_{ij} \leq 1$, and all relevant values of p_i. Therefore, all polluting firms charge the monopoly price, i.e. $P_{ij} = z$ for all i, j. The resulting output quantities are $q^*_{ij} = x^*_{ij} = f$ for all exporting firms (with $i \neq j$), and $q^*_{ii} = x^*_{ii} = d$ for all firms that sell to a domestic consumer. Accordingly, the highly stylized trade model yields *fixed consumption and production patterns* and, therefore, also fixed trade flows, provided that BCA deters firms from relocating to countries with lower carbon prices. Moreover, each of the $N-1$ firms in the export sector of country i produces the same quantity so that we obtain $\mu \equiv q^*_{ij} = f$ for the export *share* of polluting goods that are exported to each of the other countries, while the remaining output, $q^*_{ii} = 1 - \mu(N-1)$, is consumed domestically.

We now turn to countries' welfare. Emissions of country j are

$$E_j = \sum_i [(\bar{E} - a_{ij})q^*_{ij}] = \bar{E} - \mu \sum_{i \neq j} a_i - (1 - (N-1)\mu)a_j,$$

where the last step follows from $a_{ij} = a_i$ for all $j \in \{1, ..., N\}$, $q^*_{ij} = \mu$ for all $j \neq i$, and $q^*_{ii} = 1 - \mu(N-1)$ (see above). Hence, total emissions are

$$\sum_j E_j = N\bar{E} - A, \tag{38}$$

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[39] Hence, firms may have different production cost functions, but all have access to comparable abatement technologies which result in identical abatement cost functions.

where $A \equiv \sum_i \sum_j a_i q^*_{ij}$ is aggregated abatement. Moreover, $\sum_j q^*_{ij} = \sum_j x^*_{ij} = 1$ due to our earlier normalization of a country's total consumption of polluting goods to 1. Therefore, $\sum_j a_i q^*_{ij} = a_i$, yielding $A = \sum_i a_i$.

Country i's consumption of the numeraire good is (using (36))

$$y_i = \bar{Y}_i - z + \sum_j \pi_{ji} + T_i.$$

Defining $\bar{C}_i \equiv \sum_{j=1}^N C_{ji}(q^*_{ji})$ for the (now effectively fixed) total production costs of the firms located in country i, this becomes (using (37))

$$y_i = \bar{Y}_i - \bar{C}_i - \mu \sum_{j \neq i} \left[c(a_j)h + p_j(\bar{E} - a_j)\right] - (1 - (N-1)\mu)\left[c(a_i)h + p_i(\bar{E} - a_i)\right] + T_i.$$

Note, that country i's total revenues from exports and expenditures on imports cancel each other out.

Let us define the *net BCA-transfer* to country i as

$$t_i \equiv T_i - \mu \sum_{j \neq i} p_j(\bar{E} - a_j) - (1 - (N-1)\mu)p_i(\bar{E} - a_i). \tag{39}$$

Hence, t_i are country i's total tax revenues minus the tax expenditures of its firms that produce for exports and the domestic market. Country i's consumption of the numeraire good can, thus, be rewritten as

$$y_i = \bar{Y}_i - \bar{C}_i - \mu \sum_{j \neq i} c(a_j)h - (1 - (N-1)\mu)c(a_i)h + t_i. \tag{40}$$

Consumption of the numeraire good thus equals endowment minus the total production and abatement costs incurred by domestic firms, plus net BCA-transfers (as specified in the main text).

The utility of the representative consumer in country i is now $U_i = y_i + z - b\sum_j E_j$. Using (38) and (40), this yields

$$U_i = \bar{Y}_i - \bar{C}_i + z - bN\bar{E} + bA - \mu \sum_{j \neq i} c(a_j)h - [1 - (N-1)\mu]c(a_i)h + t_i.$$

Defining a constant $\kappa_i \equiv \bar{Y}_i - \bar{C}_i + z - bN\bar{E}$, we obtain $U_i = \kappa_i + \Pi_i$, where

$$\Pi_i \equiv bA - \mu \sum_{j \neq i} c(a_j)h - [1 - (N-1)\mu]c(a_i)h + t_i. \tag{41}$$

Note, that κ_i is independent of countries' abatement, participation, and R&D decisions. Therefore, the analysis in the main text is based on Π_i as the expression for country i's welfare.[40] For the case of k signatories, this yields equations (2) and (3).

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[40] It is the additional utility of the representative consumer in country i relative to the benchmark case where $a_j = 0$ is exogenously fixed for all countries j (including $j = i$).

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