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Abstract

Border carbon adjustments (BCAs) have been suggested as a measure to reduce carbon leakage in the presence of unilateral climate policies and/or to enforce cooperative climate agreements. In an intra-industry trade model, this paper studies whether and under which conditions a sequence of escalating threats of implementing BCA-measures could be successful in enforcing a fully cooperative agreement. We start from a situation where moving from non-cooperative production-based carbon taxes to a socially optimal tax is not attractive to the environmentally less concerned country. We then test whether the threat of imposing BCA-measures, in the form of import tariffs or, additionally, complemented by export rebates, will enforce cooperation. We show that import tariffs are the least distortionary policy instrument but the weakest threat, and import tariffs with a full export rebate is the most distortionary instrument if implemented but the most effective threat to enforce cooperation. In an escalating penalty game, we determine the subgame-perfect equilibrium path along which threats must be deterrent but also credible. We show that BCA-measures help to enforce cooperation, reduce global emissions and are welfare improving if they need to be implemented. However, whenever full cooperation would generate the highest global welfare gains, BCAs fail to establish cooperation, a version of the paradox of cooperation, as proposed by Barrett (1994).

Keywords: Border Carbon Adjustments, Escalating Penalties, Enforcement of Cooperation, Carbon Leakage

JEL-Classification: C7, F12, F18, Q58, H23

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1 Introduction

An effective solution to climate change requires cooperation among all countries in reducing global greenhouse gas emissions. However, strong free-rider incentives constitute a major stumbling block to reach a global agreement. Furthermore, the effectiveness of unilateral actions by some countries is weakened by carbon leakage. One of the channels of carbon leakage is the relocation of production of firms, in particular in emission-intensive trade-exposed industries, to countries with lower environmental standards. As a result, firms operating in countries with a stricter climate policy lose market shares in the domestic but also international markets.

In order to address carbon leakage and to incentivise higher carbon taxes globally, border carbon adjustments (BCAs) have been proposed (e.g., Elliott et al., 2010; Helm et al., 2012; Stiglitz, 2006). BCAs are trade measures complementing climate policies. (i) BCAs on imports levy a carbon tariff on imports from countries with lower environmental standards; (ii) BCAs on exports provide a rebate on exports to firms faced with higher environmental standards; (iii) BCAs on imports and exports, which is sometimes called full BCAs.[1] The purpose of tariffs and export rebates is to create an equal playing field - they reduce the disadvantage of firms located in countries with higher environmental standards.

Trade measures to support environmental policies can be defended, based on economic efficiency, as a second-best solution, correcting distortions resulting from the failure of internalising damages of transboundary pollution (Copeland, 1996; Helm et al., 2012; Hoel, 1996; Markusen, 1975; Stiglitz, 2006). In the absence of global action, e.g., Markusen (1975) shows that, from a purely national perspective, the optimal combination of policies is a Pigouvian tax on domestic production and a tariff on imports. Even in a cooperative setting, Keen and Kotsogiannis (2014) show that some forms of BCAs are required to achieve global Pareto-efficiency.

There are now quite some papers that focus on quantifying the impact of BCAs on carbon leakage and the competitiveness of emission intensive industries (e.g., Böhringer et al., 2014; 2015; 2017 and 2018; Fischer and Fox, 2012 and Larch and Wanner, 2017).[2] The bulk of these papers use numerical simulations, often by employing computable general equilibrium (CGE) models or integrated assessment models (IAMs). Most of these studies conclude that BCAs can effectively mitigate carbon leakage and reduce the output loss of emission intensive industries. However, most of the reduction in total emissions are driven by BCAs on imports, i.e. carbon tariffs. Besides, the role of carbon tariffs, as trade sanctions, in fostering cooperation on climate change has been studied by for instance Irfanoglu et al. (2015) using CGE models and Nordhaus (2015) using IAMs. However, due to the complicated nature of those models, carbon taxes in those countries on which BCAs are imposed are assumed to be fixed and often set to zero. Thus, these models do not capture endogenous strategic responses.

A far smaller literature is of theoretical nature and considers the role of BCAs in a non-

[1] Output-based rebating is a variant of full BCAs. Rebates are provided for domestically produced output, regardless whether consumed domestically or exported (Fischer and Fox, 2012).

[2] Some other papers focus on the legal issues of BCAs in relation to the regulation of the World Trade Organisation (WTO); see, for instance, Fischer and Fox (2012) and Mehling et al. (2019).

cooperative strategic carbon tax competition game with endogenous policy choices. Helm et al. (2012) consider a simple political BCA-game and argue that exporting countries on which carbon tariffs are imposed respond by taxing their exports rather than remaining inactive or retaliate. However, the predicted behaviour of political actors is not based on a micro-foundation of incentives and hence somehow ad hoc. Sanctuary (2018), assuming perfect competition, and Eyland and Zaccour (2014), assuming imperfect competition, show that imports tariffs are effective in pushing all countries to adjust their carbon taxes upward. Also Hecht and Peters (2018) confirms that BCAs allow the country which unilterally imposes these measures to set a higher carbon tax. However, they find that the optimal response of the country on which BCAs are imposed is to adjust its tax downward. Most likely, this latter result is due to their special assumption that tariff and export rebate rates are the same.

Another aspect is added in Anouliés (2015) and Baksi and Chaudhuri (2017). They consider the role of tariffs on imports for enforcing cooperation. Anouliés (2015) concludes that carbon tariffs support the compliance of at least one country. Baksi and Chaudhuri (2017) show that carbon tariffs can be helpful in enforcing compliance in a repeated game through trigger strategies, even though they are not always effective. However, trigger strategies have been criticized for not being robust against renegotiations (Ederington, 2002; Mason et al., 2017; Van Damme, 1989) and both papers do not consider export rebates.

This paper contributes to the theoretical literature on BCAs. We also consider the role of BCAs in enforcing cooperation. However, we model an escalating penalty game with various forms of BCAs, including import tariffs but also export rebates with different rates. We start our analysis with an initial situation in which two governments impose non-cooperatively a production-based carbon tax on their producers (PB-regime). We first show that only if the individual evaluation of environmental damages in the two countries is similar will both countries be better off under full cooperation (FC-regime). We then consider the situation when full cooperation cannot be achieved and ask the question whether and under which conditions the environmentally more concerned country can enforce cooperation through a sequence of escalating threats. We consider three threats which constitute various forms of BCAs: (1) a carbon tariff which fully adjusts the difference between the two national tax levels (BI-threat); (2) a carbon tariff combined with an export rebate which is chosen optimally and therefore may not be a full rebate (BIE-threat); (3) a carbon tariff combined with a full export rebate which implies de facto a unilateral consumption-based tax (BF-threat).

We show under which conditions a weaker punishment is sufficient to establish cooperation, under which conditions threats need to be escalated and under which conditions BCAs are not effective at all in establishing cooperation. We show that BCAs can generally be global welfare distorting, even though in equilibrium they are not. Either BCAs are deterrent enough and establish cooperation or if they are not and implemented, then they are globally welfare improving and reduce global emissions compared to the PB-regime. Hence, we conclude that BCAs are helpful in either fully internalizing a global externality by enforcing full cooperation or partially internalize a global externality if they need to be implemented. Nevertheless, we also confirm the "paradox of cooperation", as derived by Barrett (1994), in our context with trade and BCAs: whenever the global gains from cooperation would be rather significant, BCAs are not sufficient to enforce cooperation.

The remainder of the paper is organised as follows. In Section 2, we present the ingredients of our three-stage model. In the subsequent sections, Sections 3 to 5, we will analyse stages in reverse order according to backward induction. Finally, Section 6 concludes and discusses possible future research.

2 Model

We consider two countries, $i = 1, 2$, with a representative consumer and firm in each country. The two firms, $k = 1, 2$, produce a homogeneous emission-intensive good x, which generates greenhouse gas emissions. Firm 1 is located in country 1 and firm 2 is located in country 2, where firms compete in outputs, i.e., in a Cournot-fashion. Each firm supplies the home and the foreign market. The inverse demand function in market i is given by:

$$p_i(X_i) = a - X_i\,, \quad \forall\ i = 1, 2 \tag{1}$$

where p_i is the market price in market i and parameter $a > 0$ is the chock-off price. Total consumption in country i is $X_i = x_{1i} + x_{2i}$ where x_{1i} and x_{2i} are the outputs supplied by firm 1 and 2 to market i, respectively.

We solve a three-stage game by backward induction.

In the first stage, countries decide whether to implement a cooperative or non-cooperative climate policy. This stage is modelled as a sequential bargaining game. Country 1, which is the environmentally more concerned country in our model, proposes a cooperative agreement. If country 2 turns down this offer, both countries can either settle for a non-cooperative production-based tax or country 1 can use a sequence of escalating penalties in order to force country 2 to accept its proposal. Those penalties correspond to various forms of border carbon adjustments (BCAs), which represent different forms of a unilateral consumption-based tax. The BCA-regimes which we consider comprise import tariffs (BI-regime) and import tariffs supplemented by export rebates, either in the form of an optimal rebate (BIE-regime) or a full rebate (BF-regime).

In the second stage, governments simultaneously choose their emission tax, given the choice of the policy regime in stage 1. Finally, in the third stage, firms simultaneously choose their outputs for both markets. Those outputs are a function of the emission taxes implemented in both countries.

In the remainder of this section, we briefly derive equilibrium outputs of firms in the third stage as a function of what we call “effective taxes”. Then we explain the various components of countries’ welfare functions, relate those to the different policy regimes as well as their effective and equilibrium taxes.

The outcome of the third stage is a Nash equilibrium in output levels in each of the two markets. We assume completely identical firms with a linear production cost function, i.e., $C_{ki}(x_{ki}) = cx_{ki}$, with $k = 1, 2$ indicating the location of firm k and $i = 1, 2$ the market for which the good is produced. Markets are segmented. That is, firms make separate quantity decisions for the home and the foreign market. The profits of firms obtained in market 1 and market 2 are given by:

$$Market\,1:\ \pi_{11} = (p_1(X_1) - c - t_{11})x_{11} \ \&\ \pi_{21} = (p_1(X_1) - c - t_{21})x_{21}\,, \tag{2}$$

$$Market\,2:\pi_{12} = (p_2(X_2) - c - t_{12})x_{12} \ \&\ \pi_{22} = (p_2(X_2) - c - t_{22})x_{22} \tag{3}$$

where t_{11} (t_{21}) is the effective carbon tax which firm 1 (2) faces on its supply to market 1 and t_{12} (t_{22}) is the effective carbon tax which firm 1 (2) faces on its supply to market 2; $X_1 = x_{11} + x_{21}$ and $X_2 = x_{12} + x_{22}$ are the total quantities supplied to market 1 and 2, respectively. We assume a constant emission-output ratio across firms, which we normalise to 1 without loss of generality. Hence, an emission tax is de facto an output tax.

The simultaneous maximisation of profits obtained in market 1 and market 2 by both firms gives the Nash equilibrium quantities supplied by firm 1 and 2:[3]

$$Market\ 1:\ x^*_{11} = \frac{A - 2t_{11} + t_{21}}{3} \ \&\ x^*_{21} = \frac{A - 2t_{21} + t_{11}}{3}\,, \tag{4}$$

$$Market\ 2:\ x^*_{12} = \frac{A - 2t_{12} + t_{22}}{3} \ \&\ x^*_{22} = \frac{A - 2t_{22} + t_{12}}{3}\,, \tag{5}$$

with $A := a - c$, which we interpret as a market size parameter. Accordingly, profits of each firm k are given by the sum of profits obtained in market 1 and market 2:

$$\Pi^*_1 = \pi^*_{11} + \pi^*_{12} = (x^*_{11})^2 + (x^*_{12})^2 \ \&\ \Pi^*_2 = \pi^*_{21} + \pi^*_{22} = (x^*_{21})^2 + (x^*_{22})^2 \quad . \tag{6}$$

In the second stage, governments choose simultaneously the level of their carbon tax t_i based on the following welfare functions:

$$W_1 = CS_1 + PS_1 + TR_1 - D_1 + BCAI_1 - BCAE_1\,, \tag{7}$$

$$W_2 = CS_2 + PS_2 + TR_2 - D_2 \tag{8}$$

where CS_i is the consumer surplus in country i, with the consumer surplus being given by $CS_i = \frac{X_i^2}{2}$, which follows from (1), recalling that the total supply to market i is given by $X_i = x_{1i} + x_{2i}$. PS_i is the producer surplus, which is the total profit of firm k based in country i, i.e., $PS_i = \Pi^*_i$, as given in equation (6). TR_i is the tax revenue of government i imposed on the production in its country where $TR_i = t_i\,(x_{k1} + x_{k2})$.

D_i are individual damages from global greenhouse gas emissions released in the production of good x. Global damages from emissions are $D\,(e)$ where $e = X_1 + X_2$ due to the normalisation of the emission-output coefficient which is set to 1. Hence, global emissions are equal to total production, which is equal to total consumption. That is,

$$D\,(e) = de, \quad D_1 = \gamma D(e), \quad D_2 = (1-\gamma)D(e), \gamma \in [0.5, 1]\ , \tag{9}$$

with $d > 0$ a damage parameter, reflecting global marginal damages. We allow for the possibility that countries perceive or evaluate global damages from emissions differently. We assume $\gamma \in [0.5, 1]$. That is, country 1 is at least as concerned as country

[3] In Appendix A, we show that Nash equilibrium output levels always exist and are unique in each market. We also derive sufficient conditions for interior solutions.

2 about environmental damages and usually more whenever γ is strictly larger than 0.5.[4]

The other terms in the welfare function of country 1 in (7) are introduced in the course of the subsequent discussion of the different policy regimes as they are only relevant under the three non-cooperative BCA-regimes. The implications for effective and equilibrium taxes are illustrated in Table 1. All details of equilibrium and effective taxes are provided in Appendix A.

If countries fully cooperate (FC-regime), they maximise $W_1 + W_2$ with respect to a uniform tax t, ignoring the $BCAI_1$ and $BCAE_1$ term in (7). Equilibrium and effective taxes are the same and are denoted by t^{FC*}, as shown in Table 1. See AppendixA.1 for details.

The cooperative regime is contrasted with four non-cooperative regimes in this paper.

First, in the production-based regime (PB-regime), each government imposes a carbon tax on the production of its home firm. Hence, the effective tax which each firm faces in both markets is equal to the equilibrium tax imposed by its home country (see Table 1). We denote the corresponding equilibrium taxes by t_1^{PB*} and t_2^{PB*}. As it is apparent from Appendix A.2, $t_1^{PB*} > t_2^{PB*}$ if $\gamma > 0.5$, i.e., the environmentally more concerned country 1 imposes a higher production-based tax.

Table 1: Effective and Equilibrium Carbon Taxes under Cooperative and Non-Cooperative Policy Regimes

	Effective Taxes	FC	PB	BI	BIE	BF
Market 1	t_{11}	t	t_1	t_1	t_1	t_1
	t_{21}	t	t_2	t_1	t_1	t_1
Market 2	t_{12}	t	t_1	t_1	$t_1(1-\varphi^*)$	0
	t_{22}	t	t_2	t_2	t_2	t_2
Equilibrium Taxes $\forall\, i = 1, 2$		$t = t^{FC*}$	$t_i = t_i^{PB*}$	$t_i = t_i^{BI*}$	$t_i = t_i^{BIE*}$	$t_i = t_1^{BF*}$

Second, in the border carbon adjustment on imports regime (BI-regime), additionally to a production-based tax, country 1 imposes a tariff on imports from country 2. Thus, firm 1 faces the effective tax $t_1 = t_{11} = t_{12}$ as under the PB-regime. Also firm 2 faces $t_{22} = t_2$ on its supply to country 2 as above; however, the effective tax t_{21} on its export to country 1 is now given by $t_{21} = t_2 + \omega(t_1 - t_2)$. Country 1 is only allowed to impose the tariff provided $t_1 > t_2$, with ω the border tax adjustment parameter on imports (Eyland and Zaccour, 2012). That is, under the BI-regime, the term $BCAI_1$ is additionally included in country 1's welfare function with $BCAI_1 = \omega\,(t_1 - t_2)\,(x_{21})$ if $t_1 > t_2$, otherwise $BCAI_1 = 0$. We assume henceforth $\omega = 1$ for two reasons. Any value of ω above 1 would be illegal under the rules of the WTO.[5] Additionally, given the opportunity of using carbon tariffs, any value smaller than 1 would not be optimal

[4] The way we model asymmetry allows us to distinguish between the level of damages, represented by the paramter d, and the distribution of damages, represented by the parameter γ. An alternative formulation would be $D_1 = d_1 D(e)$ and $D_2 = d_2 D(e)$ with similar qualitative conclusions.

[5] The GATT allows WTO members to apply a border tax adjustment at a rate which is not higher than the rate applied to domestically produced "like" products.

for country 1.[6] The assumption $\omega = 1$ implies that both firms face the same effective carbon tax on its supply to market 1 (see Table 1). Therefore, BCAs on imports always constitute a "full adjustment" on imports. Equilibrium taxes, which follow from maximisation of each government's individual welfare function with respect to own taxes, gives t_1^{BI*} and t_2^{BI*}. See Appendix A.3 for details.

Third, in the border carbon adjustment on imports and optimal export rebate regime (BIE-regime), country 1 complements its production-based tax and carbon tariff on imports with a rebate on its firm's exports to country 2. We assume that the export adjustment/rebate rate φ is chosen optimally by government 1, i.e., φ^*. Compared to the BI-regime, the effective tax on exports of firm 1 to country 2, t_{12}, is now given by $t_{12} = t_1(1 - \varphi^*)$ provided $t_1 > t_2$, with φ^* the optimal border carbon tax adjustment parameter on exports, or, equivalently the optimal export rebate rate.[7]

According to the WTO-rule of non-discrimination, $t_1(1-\varphi^*) \geq t_2$ must hold. Generally speaking, the optimal φ^* can be positive or negative and can be smaller or larger than 1. Later, we clarify the range of φ^*. At this stage it suffices to point out that it is neither obvious that φ^* is chosen such that $t_1(1 - \varphi^*) = 0$ (full rebate) nor such that $t_1(1-\varphi^*) = t_2$ (full adjustment) because subsidising exports is costly. Under the BIE-regime, the term $BCAE_1$ is additionally included in country 1's welfare function with $BCAE_1 = \varphi^* \, t_1 \, x_{12}$ if $t_1 > t_2$ and $t_1(1-\varphi^*) \geq t_2$, otherwise $BCAE_1 = 0$. Equilibrium taxes follow from the individual maximisation of welfare functions with respect to own taxes, leading to t_1^{BIE*} and t_2^{BIE*}. See Appendix A.4 for details.

Fourth, the border carbon adjustment on imports and full export rebate regime (BF-regime) is similar to the BIE-regime, except that the rebate rate on exports φ is not chosen optimally but set to one, i.e., $\varphi= 1$. Hence, firm 1 faces effective tax $t_{12} = 0$ on its exports and the WTO-rule requires $t_{12} \geq t_2$. Equilibrium taxes are given by t_1^{BF*} and t_2^{BF*}. See Appendix A.5 for details.

3 Third Stage

In this section, we have a closer look at the effect of taxes on equilibrium output levels. These effects are straightforward in the fully cooperative regime with a uniform tax. All output levels for each market are the same. Increasing the tax gradually lowers all outputs uniformly, decreases profits and consumer surplus uniformly, increases tax revenues and decreases damages uniformly, even though, country 1 benefits more than country 2 from lower damages as long as $\gamma > 0.5$.

In the non-cooperative policy regimes, taxes in country 1 and 2 will be generally different and also the effects of taxes on outputs.

[6] That is, if ω could be chosen endogenously under the restriction $\omega \leq 1$, $\omega^* = 1$. See for instance Hecht and Peters (2018).

[7] Note that we cannot model BCAs on exports in the same way as on imports. That is, we cannot assume for instance $t_{12} = t_1 - \varphi(t_1 - t_2)$ because country 2 does not tax firm 1.

Proposition 1. The Effect of Non-Cooperative Taxes on Equilibrium Production and Consumption

i. The production of firm 1 (firm 2) for market 1:

- *decreases (increases) in the tax of country 1, while it increases (decreases) in the tax of country 2 under the PB-regime;*
- *decreases (decreases) in the tax of country 1 and it is independent (independent) of the tax of country 2 under all BCA-regimes.*

ii. The production of firm 1 (firm 2) for market 2:

- *increases (decreases) in the tax of country 2 under all regimes;*
- *decreases (increases) in the tax of country 1 under the PB- and the BI-regime, and under the BIE-regime if $\varphi^* < 1$;*
- *increases (decreases) in the tax of country 1 under the BIE-regime if $\varphi^* > 1$;*
- *is independent (independent) of the tax of country 1 under the BF-regime.*

iii. The consumption in both markets:

- *decreases in the tax of both countries under the PB-regime;*
- *Under all BCA-regimes:*
  - *the consumption in market 1 decreases in the tax of country 1, while it is independent of the tax of country 2;*
  - *the consumption in market 2 always decreases in the carbon tax of country 2, decreases (increases) in the tax of country 1 if $\varphi^* < 1$ ($\varphi^* > 1$) under the BIE-regime, and is independent of the tax of country 1 under the BF-regime.*

Proof. Follows from inserting the effective taxes in Table 1 into (4) and (5) and differentiating output with respect to tax levels. □

Under the PB-regime, the standard effects as known from the literature hold: the production of each firm decreases in its domestic tax while it increases in the foreign tax. Consumption levels in both markets are negatively affected by both taxes. Therefore, firm 1, facing a higher equilibrium carbon tax than firm 2 if $\gamma > 0.5$, is less competitive in both markets, though the consumer surplus is the same in both countries.

With an import tariff, which is part of all three BCA-regimes (BI-, BIE- and BF-regime), country 1 fully controls the output supplied to its home market. Taxes on the supply to country 1 are fully adjusted through import tariffs. Therefore, all outputs produced for market 1 (and hence also consumption in country 1) are negatively affected by tax t_1 and are independent of tax t_2. Thus, profits in market 1 are the same for both firms, though profits in market 2 are still lower for firm 1 than firm 2 (because $t_1 > t_2$ by assumption under these regimes). It is also clear that consumers in country 1 enjoy a lower consumer surplus because the supply to market 1 is lower than to country 2.

If a carbon tariff is supplemented by an export rebate under the BIE- and BF-regime, the output of firm 1 (firm 2) sold to market 2 is still negatively (positively) affected by the tax in country 1 if $\varphi^* < 1$, which is one possibility under the BIE-regime, though to a lesser extent than under the PB- and BI-regime and is unaffected by the tax in country 1 if $\varphi = 1$ as under the BF-regime and even increases (decreases) in t_1 if $\varphi^* > 1$, which is another possibility under the BIE-regime.[8] The same relations are found for total consumption in market 2. However, regardless of the value of φ, firm 1's profits will be (weakly) lower than firm 2's profits in market 2 because we have $t_1(1-\varphi) \geq t_2$ by assumption. Thus, export rebates will usually not level the playing field in market 2, though they lower the difference in profits between the two firms. Accordingly, also the difference in consumer surpluses in the two countries, as observed under the BI-regime, will remain and, in fact, may be even become larger as exports to market 2 are subsidised under the BIE- and BF-regime. Interestingly, under the BF-regime, which is de facto a unilateral consumption-based tax, the consumption in each market is independent of the foreign country's tax level.

Thus, moving from the PB-regime to the BI-regime, raises profits of firm 1 in market 1, but disadvantages consumers in country 1. Moving from the BI-regime to the two regimes with export rebates (BIE- and BF-regime) improves upon the profits of firm 1 in market 2, but drives a further wedge between the consumer surplus enjoyed in market 1 and 2. Of course, in order to understand how the different regimes impact on the welfare levels of both countries, equilibrium tax levels need to be considered, which is part of the second stage of the three stage game and treated in Section 4. Moreover, taxes, tariffs and rebates do not only affect producers and consumers, but also affect revenues of governments. Finally, one motivation of BCAs is the possibility of reducing environmental damages. On the way of clarifying this issue, we offer Proposition 2.

Proposition 2. The Effect of Non-Cooperative Carbon Taxes on Global Emissions

- $\frac{\partial e^{PB}}{\partial t_1} = \frac{\partial e^{PB}}{\partial t_2} < 0.$
- *The carbon tax of country 1 has the largest impact on reducing global emissions under the BI-regime:*

  i. $\left|\frac{\partial e^{PB}}{\partial t_1}\right| = \left|\frac{\partial e^{BF}}{\partial t_1}\right| \leq \left|\frac{\partial e^{BIE}}{\partial t_1}\right| < \left|\frac{\partial e^{BI}}{\partial t_1}\right| < 0 \text{ if } 0 \leq \varphi^* \leq 1,$

  ii. $\left|\frac{\partial e^{BIE}}{\partial t_1}\right| < \left|\frac{\partial e^{PB}}{\partial t_1}\right| = \left|\frac{\partial e^{BF}}{\partial t_1}\right| < \left|\frac{\partial e^{BI}}{\partial t_1}\right| < 0 \text{ if } 1 < \varphi^* < 3$ *,and*

  iii. $\frac{\partial e^{BIE}}{\partial t_1} \geq 0 \text{ if } \varphi^* \geq 3$

  where φ^* denotes the optimal rebate rate under the BIE-regime and the rebate rate under the BF-regime is by assumption $\varphi = 1$.

[8]Overcompensating firms is not uncommon. For example, Martin et al. (2014) show that the free allocation of emission permits under the European Union Emissions Trading Scheme (EU-ETS) resulted in sizeable overcompensation of emission-intensive industries.

- *The carbon tax of country 2 has a lower impact on reducing global emissions under the BCA-regimes than under the PB-regime:* $\left|\frac{\partial e^{BF}}{\partial t_2}\right| = \left|\frac{\partial e^{BIE}}{\partial t_2}\right| = \left|\frac{\partial e^{BI}}{\partial t_2}\right| < \left|\frac{\partial e^{PB}}{\partial t_2}\right| < 0$.

Proof. Follows from inserting the effective taxes in Table 1 into (4) and (5) and differentiating total output with respect to taxes, recalling that we assume a constant emission-output ratio equal to 1. □

Under the PB-regime, the emission taxes of both governments have the same impact on reducing global emissions. Moving from the PB- to the BI-regime, the emission tax in country 1 has a stronger impact on reducing global emissions as it now controls not only its domestic production but also imports. Adding export rebates may partially (if $0 \leq \varphi^* < 1$) or completely (if $\varphi = \varphi^* = 1$) offset the effect of taxes in country 1 on reducing global emissions. In fact, for $\varphi^* > 1$, the effect of taxes t_1 on reducing global emissions is even lower than under the PB-regime. Hence, complementing carbon tariffs with export rebates reduces the environmental effectiveness of taxes in country 1, even though it may reduce leakage effects caused by country 2 and may also improve the welfare position of country 1. In contrast, BCA-measures generally weaken the impact of country 2's tax on global emissions. Thus, in order to have the full picture how the different regimes impact on producers, consumers, revenues and damages and hence on the strategic interaction among the two countries including leakage effects, we need to consider the second stage. In particular, we need to solve for equilibrium taxes under the different regimes and the equilibrium export rebate rate under the BIE-regime.

4 Second Stage

In the second stage, governments choose their climate policy level cooperatively or non-cooperatively. In Appendix A, we derive equilibrium taxes under the full cooperative regime (FC-regime) and the four non-cooperative regimes (PB-, BI-, BIE- and BF-regime). We establish existence and uniqueness of equilibria. We also derive what we call non-negativity constraints (NN-constraints) and border carbon adjustment constraints (BCA-constraints) that impose conditions on the parameters of our model. NN-constraints are simply conditions such that all output levels are positive. Hence, they establish interior solutions. Typically, they require β to be larger than some threshold $\check{\beta}(\gamma)$ with $\beta := \frac{A}{d}$ and $A := a - c$. We recall that A is a measure of the market size in our model, or, a proxy of the net benefits of production and consumption whereas d is the parameter that evaluates damages. Hence, if d was too large in relation to A (i.e., $\beta < \check{\beta}(\gamma)$), equilibrium taxes would imply negative outputs. BCA-constraints ensure that equilibrium taxes in country 1 are higher than in country 2 in accordance with the fundamental assumption under the BCA-regimes. Such conditions can also be expressed in terms of β to be smaller than some threshold $\hat{\beta}(\gamma)$. Whenever we conduct a comparison across regimes, we assume the most restrictive NN- and BCA-constraints to hold. See in particular Appendix A.6.

In Appendix A, we also derive reaction functions under the non-cooperative regimes, which are illustrated in Figure 1. We refer to country 1's reaction function as RF_1 and that of country 2 as RF_2. Figure 1 assumes particular parameter values, but the sign of the slope of the reaction functions (though not the slope itself) would be the same for other parameter values.

In panel (a) in Figure 1, reaction functions under the PB-regime are shown. As expected, reaction functions are downward sloping implying that taxes are strategic substitutes. In panel (b) and (c) reaction functions under the three BCA-regimes are drawn. The reaction function of country 2, the country on which the BCA-measures are unilaterally imposed, remains downward sloping. In contrast, country 1' reaction function becomes upward sloping for all $t_1 > t_2$, which is the region below the 45°-line.

Under all BCA-regimes, not only country 1's but also country 2's reaction function is a piecewise reaction function with a jump at the 45°-line. For country 1, with $RF_1 := t_1(t_2)$, there is a level $\bar{t_2}$ for which matching taxes, i.e., $t_1(\bar{t_2}) = \bar{t_2}$ is a best response. At this point and for any higher tax t_2, the reaction function jumps from the BCA-regime to the PB-regime as now $t_1(t_2) \leq t_2$. A similar explanation applies to the reaction function of country 2, $RF_2 := t_2(t_1)$ (see the details in Appendix A.7).

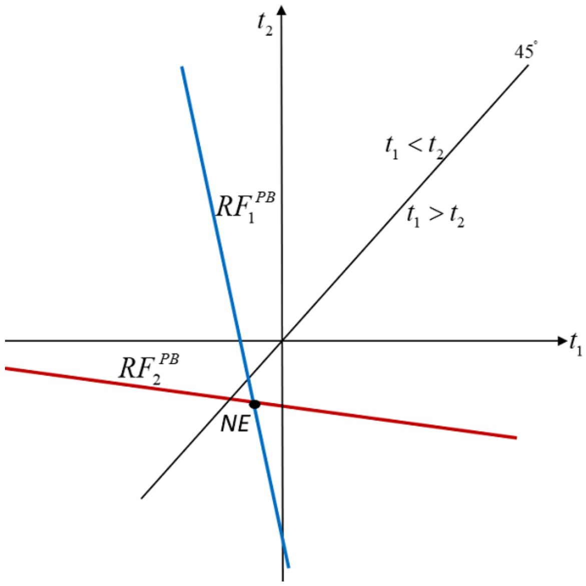
Adding import tariffs to the PB-regime, as done under the BI-regime, implies that carbon taxes become strategic complements for country 1 (see panel (b) in Figure 1). The intuition is as follows. First, unlike under the PB-regime, t_2 has no effect on consumption in country 1. Second, the impact of t_2 on global emissions becomes smaller compared to the PB-regime (and the impact of t_1 larger; see Proposition 2). As a result, increasing t_2 is not sufficient to reduce damages in country 1. Hence, country 1 responds by raising its tax. Third, carbon tariffs revenues create a new incentive for country 1 to tax emissions. Recalling that tariff revenues depend on the difference between the two tax levels, country 1 raises its tax level t_1 if t_2 increases in order to obtain higher tariff revenues.

The reaction function of country 2, RF_2, remains downward sloping, though it becomes steeper under the BI-regime for t_1 sufficiently large, i.e. below the 45°-line (see panel (b) in Figure 1). There are two opposing effects. First, country 2 has a lower incentive to reduce its carbon tax level with increasing t_1 in order to protect its tax revenues, which are partly captured by country 1 under the BI-regime. Second, country 2 has a higher incentive to reduce its carbon tax level with increasing t_1 as t_1 also harms consumers in country 2. Moreover, it reduces the profits of firm 2 obtained in market 1 as firm 2 faces t_1 on its exports. The overall effect is that country 2 reduces its tax more strongly than under the PB-regime for any marginal increase of t_1.

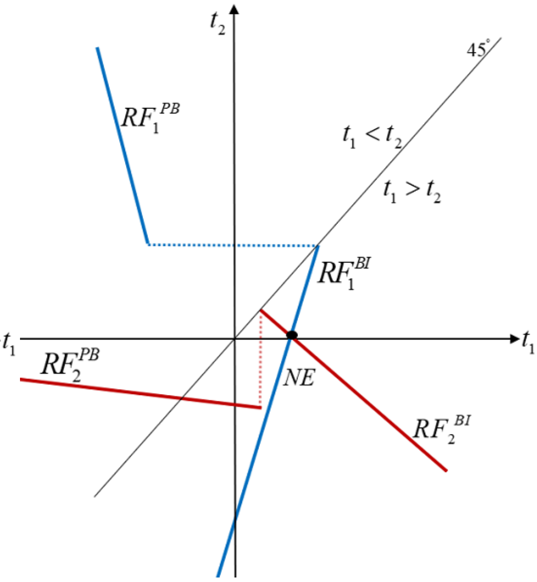
Under the BIE-and BF-regime, adding export rebates to import tariffs, the slope of country 1's reaction function RF_1 remains upward sloping and country 2's reaction function does not change.[9]

We conclude the above discussion with Proposition 3, which ranks the Nash equilibrium emission taxes across the different regimes.

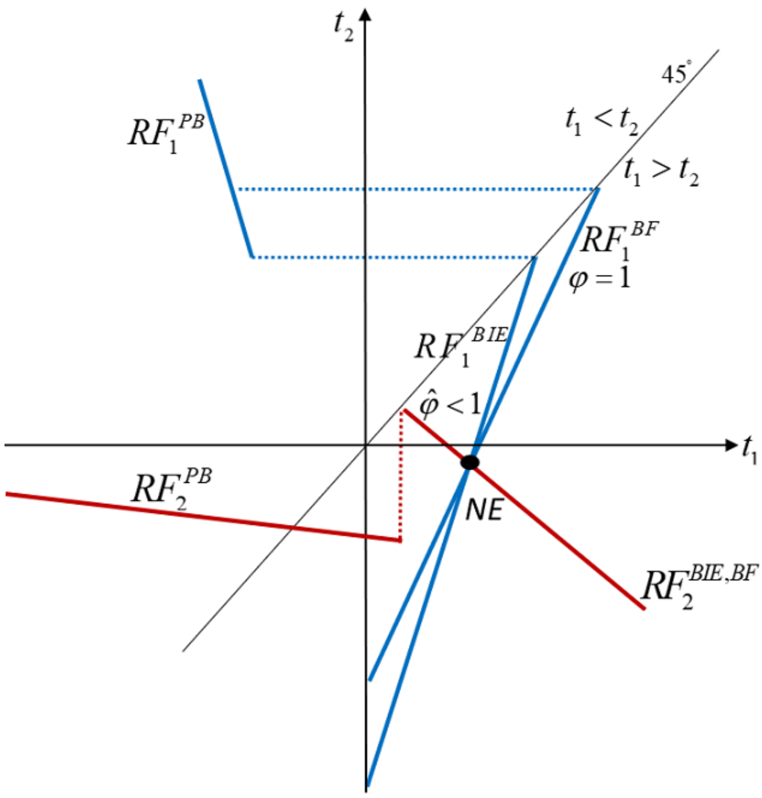
[9] See Appendix A.7.



(a) PB-regime



(b) BI-regime



(c) BIE- and BF-regime

Figure 1: Reaction Functions of Countries under Non-cooperative Regimes
*The reaction functions are drawn assuming $A = 10$, $d = 3$ and $\gamma = 0.7$.

Proposition 3. Ranking of Equilibrium Carbon Taxes

i. Equilibrium taxes in country 1 can be ranked as follows: $t_1^{PB*} < t_1^{BI*} < t_1^{BIE*} = t_1^{BF*}$.

ii. Equilibrium taxes in country 2 can be ranked as follows: $t_2^{PB*} < t_2^{BIE*} = t_2^{BF*} < t_2^{BI*}$.

iii. Under the BIE-regime, $\varphi^* > 0$ *and* $\varphi^* \leq (>) 1$ *if* $\beta \leq (>) \ddot{\beta}(\gamma)$ *with* $\beta := \frac{A}{d}$.

iv. The effective taxes of country 1 in market 1 are the equilibrium taxes in country 1. Hence, $t_{11}^{PB*} < t_{11}^{BI*} < t_{11}^{BIE*} = t_{11}^{BF*}$.

The effective taxes of country 1 in market 2 can be ranked as follows:
a) $t_{12}^{PB*} < t_{12}^{BIE*} < t_{12}^{BI*}$, *b)* $t_{12}^{BF*} < t_{12}^{BI*}$, *c)* $t_{12}^{BF*} \leq (>) t_{12}^{BIE*}$ *if* $\varphi^* \leq (>) 1$ *and d)* $t_{12}^{BF*} \leq (>) t_{12}^{PB*}$.

v. The effective taxes of country 2 in market 1 are the equilibrium taxes of country 1, except for the PB-regime. Thus, $t_{21}^{PB*} < t_{21}^{BI*} < t_{21}^{BIE*} = t_{21}^{BF*}$.

The effective taxes of country 2 in market 2 are the equilibrium taxes in country 2. Hence, $t_{22}^{PB*} < t_{22}^{BIE*} = t_{22}^{BF*} < t_{22}^{BI*}$.

vi. The socially optimal tax level is always larger than the non-cooperative taxes under the PB-regime: $t_i^{PB*} < t^{FC*}\ \forall\ i = 1, 2$. *This is normally also the case under the BCA-regimes, even though* $t^{FC*} < t_i^{BI*}, t_i^{BIE*}, t_i^{BF*}$ *is possible for one or both countries if global marginal damages* d *are relatively small compared to the market size* A*, i.e.,* β *sufficiently is large.*

Proof. See Appendix A.8, including the precise definitions of $\ddot{\beta}(\gamma)$. □

Proposition 3 makes a distinction between equilibrium taxes and effective taxes.[10] The reason is that firm 2 faces de facto not tax t_2 but tax t_1 on all exports to market 1 under all BCA-regimes. Moreover, firm 1 faces de facto not t_1 but $t_1(1 - \varphi)$ on all exports to market 2 under the BIE- and BF-regime, with $\varphi = \varphi^* > 0$ as we learn from Proposition 3 under the BIE-regime and $\varphi = 1$ by assumption under the BF-regime. That is, the effective tax of country 1 levied on its firm's exports is lower than the equilibrium tax.

Proposition 3 clearly shows that country 1 chooses higher equilibrium taxes if BCA-measures are available. BCA-measures improve the competitiveness of its firm. Moreover, it controls a larger share of global emissions. That is, country 1 can better address carbon leakage. Thus, country 1 is more effective in internalising its environmental damages. Additionally, tariffs provide a source of revenues.

The effective tax of country 1 in market 1 is higher under the BIE- and BF-regime than under the BI-regime, but in market 2 this is reversed. Thus, country 1 compensates higher effective taxes in market 1 with lower effective taxes in market 2 if export rebates are available. It is possible that the effective tax of country 1 in market 2 under the BF-regime is even lower than under the PB-regime, i.e., $t_{12}^{BF*} < t_{12}^{PB*}$. This could be the case if the damage evaluation parameter d is sufficiently large compared to

[10] The fact that equilibrium taxes under the BIE- and BF-regime are equal is due to our assumption of a linear damage function.

the evaluation parameter A of the net benefits from the production and consumption, such that $\beta = A/d$ is sufficiently small.

The ranking of the effective taxes of country 1 in market 2 under the BIE- and BF-regime simply depends on whether φ^* is larger or smaller than 1 under the BIE-regime where we recall that $\varphi = 1$ under the BF-regime. If β is sufficiently small, i.e., $\beta < \ddot{\beta}(\gamma)$, then φ^* will be smaller than 1 and $t_{12}^{BF*} < t_{12}^{BIE*}$. Apart from balancing net benefits and damages when choosing the optimal export rebate rate φ^*, export rebates are costly to country 1. This explains why it may be rational to choose an export rate smaller than 1, i.e., $\varphi^* < 1$.

Country 2 also chooses higher equilibrium taxes under the BCA-regimes than under the PB-regime. Of course, the country 2's effective taxes in market 1 are those of country 1 due to fully adjusted import tariffs. However, even its effective taxes in market 2 are higher under the BCA-regimes than under the PB-regime. Country 2 has an incentive to protect is tax revenues if faced with an import tariff. This effect is weakened with export rebates, as country 2 tries to protect the competitiveness of its firm in its home market, but still its effective tax is higher than under the PB-regime. Hence from country 1's perspective, BCAs are effective in reducing global emissions and the leakage effect caused by country 2.

Finally, full cooperation among countries always implies to higher equilibrium carbon taxes than in the non-cooperative PB-regime. However, since BCAs create incentives for both countries towards setting higher taxes, equilibrium taxes may be even higher than under full cooperation. Important for the understanding of this result is that the socially optimal tax is not equal to global marginal damages in a Pigouvian sense due to imperfect competition.[11] Both governments could set higher taxes under the BCA-regimes than in the social optimum when global marginal damages d are low compared to the net benefits from production and consumption A.[12] In such cases, socially optimal taxes will be low but BCAs still provide a sufficiently high incentive to both countries to choose high non-cooperative taxes for strategic reasons.

It is obvious from the above results that global emission levels generally decrease with import tariffs under the BCA-regimes compared to the PB-regime. However, the effect of adding export rebates to carbon tariffs is a priori ambiguous. The following Proposition ranks global emission levels across the BCA-regimes.

Proposition 4. Ranking of Equilibrium Global Emissions

- *BCA-regimes vs PB-regime:* $e^{BI*}, e^{BIE*}, e^{BF*} < e^{PB*}$.
- *Across the BCA-regimes:*
  - $e^{BI*} < e^{BIE*}$ *and* $e^{BI*} \gtreqless e^{BF*}$;
  - $e^{BIE*} \leq (>) e^{BF*}$ *if* $\varphi^* \leq (>) 1$, *which corresponds to* $\beta \leq (>) \ddot{\beta}(\gamma)$ *with* $\beta := \frac{A}{d}$.

[11] This result is well-known in the literature, see, e.g. Barnett (1980), Conrad (1993) and Kennedy (1994).

[12] For a qualitatively similar result, see Baksi and Chaudhuri (2017).

Proof. See Appendix A.9, including the precise definition of $\ddot{\beta}(\gamma)$. $\square$

All BCA-regimes reduce global emissions compared to the PB-regime. BCAs with export rebates are less effective in that despite rebates support the climate policy of country 1 (i.e., they reduce carbon leakage and protect its firm's competitiveness). Equilibrium global emissions are higher under the BIE-regime than under the BI-regime. This result confirms the main argument against export rebates. They are less effective in reducing global emissions. Only under the BF-regime with a full rebate it is possible that global emissions could be lower than under the BI-regime, but as we show in Appendix A.9, only if the damage evaluation d is very small compared to the benefit evaluation of production and consumption A in our model. As Proposition 5 will confirm, these are parameter constellations when the gains from cooperation are small.

Although studying the effects of BCAs on global emissions is important, given that these measures have been proposed for environmental reasons, we need to investigate their impacts on welfare. From a normative point of view, this is relevant because BCAs do not only affect environmental damages, but also trade and hence production and consumption. From a positive point of view, it is relevant in order to understand the incentive of countries of implementing a cooperative climate policy. Given that BCAs are unilateral measures, one intuitively expects that effects for the two countries are different and may even go in opposite directions (e.g., Böhringer et al. (2018) and Larch and Wanner (2017)). Hence, if there are winners and losers, BCAs may lead to ambiguous global welfare effects.

Proposition 5. Ranking of Equilibrium Welfare

Let $W^* = W_1^* + W_2^*$ be equilibrium global welfare and recall $\beta := \frac{A}{d}$ and $A := a - c$.

1) FC-regime vs PB-regime:

- $W_1^{FC*} > W_1^{PB*}$.
- $W_2^{FC*} \geq (<) W_2^{PB*}$ *if* $\gamma \leq (>) \overline{\gamma} = \frac{41}{64} \simeq 0.64$.
- *Let* $\Delta W = W^{FC*} - W^{PB*}$, *then* ΔW *decreases in* β.

2) BCA-regimes vs PB-regime:

- $W^{BI*} > W^{PB*}$ *except if* $\beta > \underline{\beta}_W^{BI}(\gamma)\ \ \forall \gamma > \underline{\gamma}_1$.
- $W^{BIE*} > W^{PB*}$ *except if* $\beta > \underline{\beta}_W^{BIE}(\gamma)\ \ \forall \gamma > \underline{\gamma}_2$.
- $W^{BF*} > W^{PB*}$ *except if* $\beta > \underline{\beta}_W^{BF}(\gamma)\ \ \forall \gamma > \underline{\gamma}_3$.
  with $\underline{\beta}_W^{BI} > \underline{\beta}_W^{BIE} > \underline{\beta}_W^{BF}$ *and* $\underline{\gamma}_1 > \underline{\gamma}_2 > \underline{\gamma}_3$.
- *Compared to the PB-regime, country 1 is always better off under all BCA-regimes and country 2 is better off if* γ *is sufficiently small and worse off if* γ *is sufficiently large.*

3) Across the BCA-regimes:

- $W^{BI*} > W^{BIE*}$ *and* $W^{BI*} > W^{BF*}$.
- $W^{BIE*} \geq (<) W^{BF*}$ *if* $\varphi^* \leq (>) 1$ *which corresponds to* $\beta \leq (>) \ddot{\beta}(\gamma)$ *with* $\beta := \frac{A}{d}$

Proof. See Appendix A.10, including the precise definition of $\ddot{\beta}(\gamma)$. □

Regarding the first part of Proposition 5, axiomatically, global welfare in the social optimum is strictly larger than under any other regime. Given our assumption of $\gamma \in [0.5, 1]$, it is not surprising that if γ is larger than some threshold $\gamma > \overline{\gamma}$, country 2 would be worse off under full cooperation compared to the PB-regime. That is, the portion $(1-\gamma)$ of the benefits from emission reduction in the form of reduced damages accruing to country 2 is too small to make up for the costs of lower production and consumption. In Section 5, we take this as a defining feature why cooperation is difficult to implement, i.e., we assume $\gamma > \overline{\gamma}$ as the starting point of our analysis. At this point, it suffices to demonstrate that moving from a non-cooperative production-based tax to a fully cooperative production-based tax, the potential global gain from cooperation ΔW decreases in β. That is, full cooperation matters if β is small, i.e., the damage parameter d is large compared to the net benefits from the production and consumption parameter A.

The second part of Proposition 5 highlights that global welfare generally increases with BCA-measures compared to the PB-regime. However, there are exceptions. As country 1 is always better off with the implementation of BCA-measures than in the PB-regime, those exceptions occur if country 2 is worse off under the BCA- than PB-regime. Country 2 is always worse off if its individual damage evaluation is low, i.e., γ is high, as it benefits very little from the reduction of global emissions under the BCA-regimes in the form of reduced damages. For intermediate values of γ, country 2 is also worse off if β is sufficiently large, as the reduction of damages cannot compensate for the loss of the net benefits from production and consumption. Only for lower values of γ, implying that countries are not too asymmetric, will also country 2 be better off under the BCA- than PB-regime. (For details, see Appendix A.10). All together, BCAs increase global welfare compared to the PB-regime when full cooperation would matter, i.e., β is not too large and the asymmetry of damages is not too pronounced.

The ranking of thresholds $\underline{\beta}_W^{BI} > \underline{\beta}_W^{BIE} > \underline{\beta}_W^{BF}$ and $\underline{\gamma}_1 > \underline{\gamma}_2 > \underline{\gamma}_3$, as listed in the second part of Proposition 5, together with the results listed in the third part of Proposition 5 suggests that the implementation of the BI-regime causes less global welfare distortions than the two BCA-regimes which also include export rebates. Moreover, the parameter range in which the BIE-regime causes distortions is smaller than the BF-regime. Finally, whenever the gains from global cooperation would be large (i.e., β is sufficiently small), global welfare is higher under the BIE- than BF-regime (as $\varphi^* < 1$). Thus, when enforcing cooperation through a threat of escalating penalties, one should proceed along the sequence BI-, BIE- and BF-regime in order to minimise the distortions in case those threats need to be implemented, an idea that we take up in Section 5.

5 First Stage

5.1 Preliminaries

In this section, we solve the first stage of the game. We ask the question under which conditions can BCAs enforce full cooperation and under which conditions is this not possible. We derive the equilibrium path in a sequential escalating penalty game in subsection 5.2 and evaluate equilibria from a global welfare perspective in subsection 5.3. In subsection 5.4, we evaluate the robustness of our conclusions for alternative assumptions.

The escalating game we have in mind is a sequential game with multiple stages as shown in Figure 2. In each stage, country 1 moves first and then country 2. In order to render the analysis interesting, we make the following assumption.

Assumption:

Country 2 has no incentive to fully cooperate if the alternative is the PB-regime. That is, $\gamma > \overline{\gamma}$ with $\overline{\gamma}$ as defined in Proposition 5.

That is, in stage 0, country 1's proposal "cooperation" is turned down by country 2. Recall that country 1 is always better off under full cooperation than under the PB-regime (see Proposition 5). Hence, the equilibrium path in stage 0 is the bold highlighted branch which directly leads to stage I. That is, the interesting part of the game starts in stage I.

In stage I, the escalating penalty game starts. Country 1 threats with the implementation of import tariffs under the BI-regime if country 2 does not accept cooperation. If country 2 accepts, the game ends at node 4 in Figure 2. If country 2 declines, the game proceeds to stage II.

In stage II, country 1 can either implement its threat as announced in stage I, i.e. it imposes the BI-regime, and the game ends at node 5, or, it can instead escalate the threat to enforce cooperation, with the threat to impose the BIE-regime. Country 2 can either give in to the BIE-threat and cooperate in which case we end up at node 6 or it refuses and the game proceeds to stage III.

In stage III, country 1 either implements the BIE-threat as announced in stage II and the game terminates at node 7 or it escalates the threat to the BF-threat. If country 2 gives in, cooperation is established at node 8. If country 2 still refuses, country 1 will implement the BF-threat and the game ends at node 9. Alternatively, one could assume that country 1 will implement its most preferred BCA-regime in this terminal stage, which, as we will show later, will depend on the parameters of the model.

As will be evident from the analysis below, there is a unique equilibrium path for each possible parameter range in our model. The sequence depicted in Figure 2 is motivated by our analysis in Section 4, in particular Proposition 5. The enforcement game starts with the least distortionary threat should it be implemented and only escalates the threat should this prove necessary, i.e., country 2 does not accept cooperation. We solve the game by backward induction in order to derive the subgame-perfect Nash equilibrium.

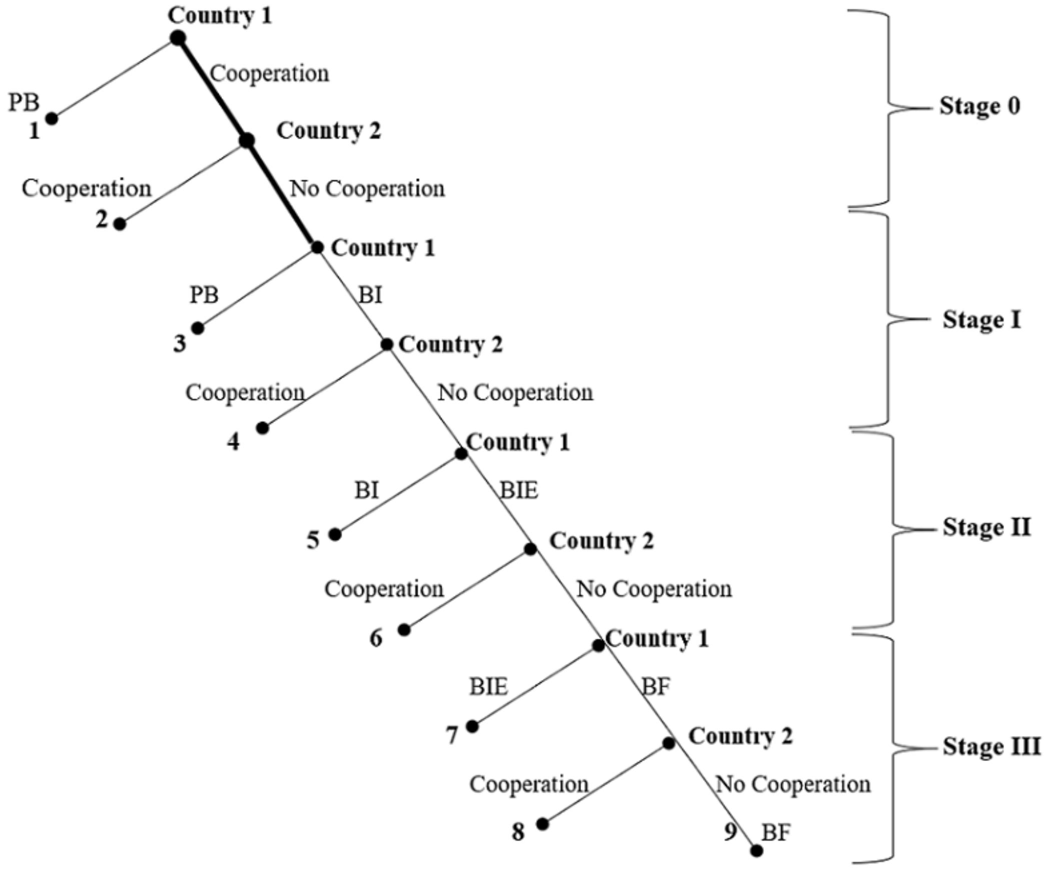


Figure 2: Escalating Penalty Game

5.2 The Equilibrium Escalating Penalty Path

For the analysis of the equilibrium path, two features are central. The first feature relates to escalating penalties. We ask the question under which conditions will country 2 accept cooperation for a particular threat and under which conditions will it refuse to cooperate. The second feature is the credibility of threats. We ask the question whether and under which conditions country 1 has an incentive to escalate penalties. The first question is answered in Lemma 1.

Lemma 1. The Effect of BCAs on the Incentive of Country 2 to Cooperate

i. Under the threat of BCAs with tariffs on imports (BI-threat), country 2 is willing to cooperate if $\beta \geq \underline{\beta_1}(\gamma)$.

ii. Under the threat of BCAs with a tariff on imports and an optimal export rebate (BIE-threat), country 2 is willing to cooperate if $\beta \geq \underline{\beta_2}(\gamma)$.

iii. Under the threat of BCAs with a tariff on imports and a full export rebate (BF-threat), country 2 is willing to cooperate if $\beta \geq \underline{\beta_3}(\gamma)$.

We have: $\underline{\beta_1}(\gamma) > \underline{\beta_2}(\gamma) > \underline{\beta_3}(\gamma)$ *with* $\beta := \frac{A}{d}$.

Proof. See Appendix B.1. □

Lemma 1 is illustrated in Figure 3. On the vertical axis, we have parameter β. On the horizontal axis, we have parameter γ. The upward sloping straight line 'BCA-C' is the BCA-constraint, implying that only values below this line satisfy the BCA-constraint. The upward sloping straight line 'NN-C', starting at $\gamma \approx \overline{\gamma} = 0.64$, is the non-negativity constraint, implying that only parameter values above this line satisfy this constraint.

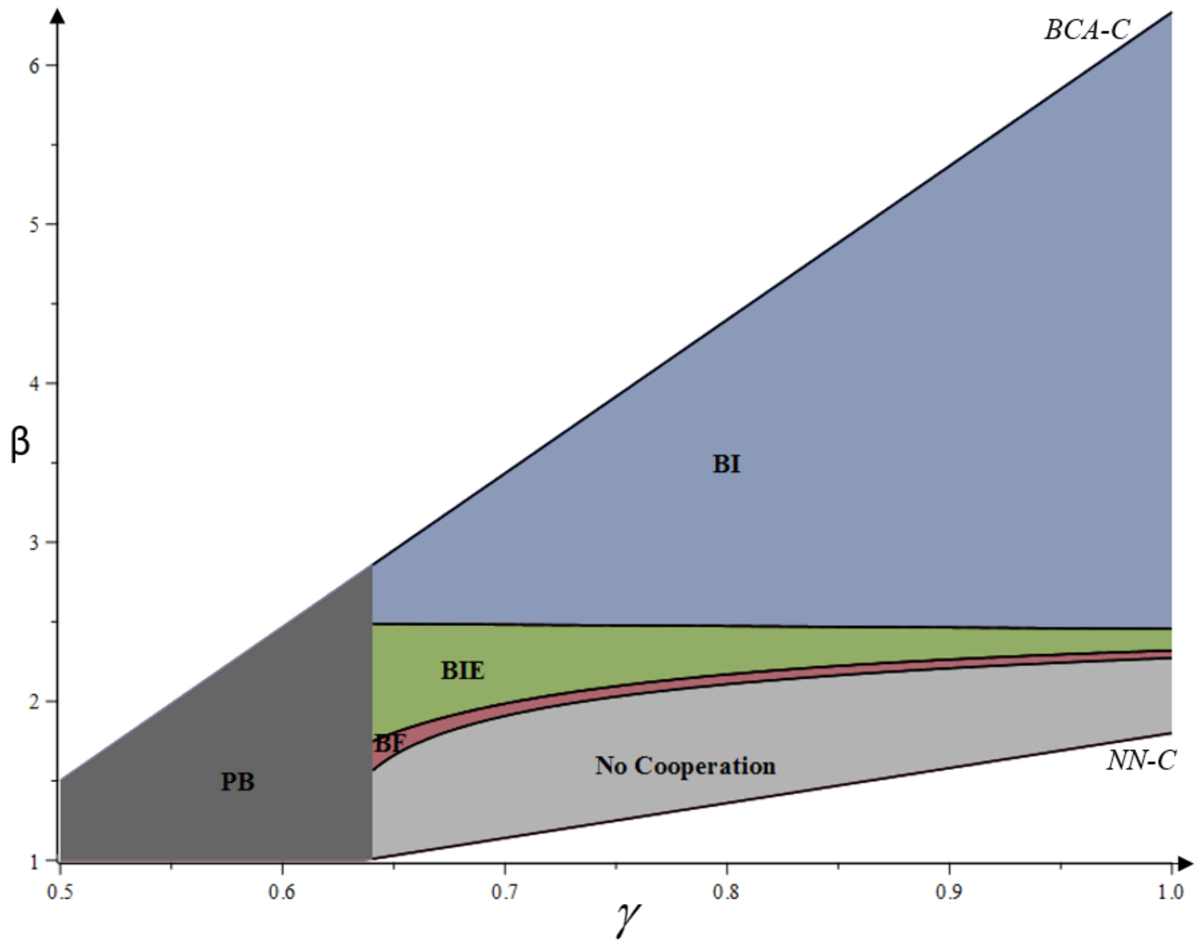


Figure 3: The Effect of BCAs on the Incentive of Country 2 to Cooperate
*BCA-C and NN-C are the BCA-constraint and the non-negativity constraint, respectively.

The black area denoted by PB is the parameter range in which country 2 would cooperate if faced with the alternative of the PB-regime. We know this would only happen if $\gamma \leq \overline{\gamma}$, which we have ruled out by assumption. The blue area denoted by BI is the parameter range in which the BI-threat enforces cooperation, i.e., condition i in Lemma 1 holds. The green area denoted by BIE is the additional parameter space in which cooperation can be enforced with the BIE-threat. That is, condition ii in Lemma 1 holds in the blue and green area. The red area is the additional parameter space in which the BF-threat is successful to establish cooperation. Thus, condition iii in Lemma 1 comprises the blue, green and red area. Finally, the grey area is the parameter space in which condition iii in Lemma 1 does not hold. Thus, Lemma 1 confirms the logic that escalation proceeds along the BI-, BIE- and BF-threat.

The decision of country 2 to cooperate if it faces the BCA-threats depends on parameters β and γ. Only if β exceeds the threshold $\underline{\beta}(\gamma)$ can cooperation be enforced. That is, whenever the gains from global cooperation would be really large, i.e., β is small according to Proposition 5, cooperation cannot be established. This has some resemblance with the paradox of cooperation as established by Barrett (1994), which we will further pursue below.

The second issue that we need to address is the credibility of threats. In stage I, country 1 must be better off under full cooperation than under the PB-regime in order for the BI-threat to be credible. With reference to Figure 2, country 1's welfare at node 4 must be higher than at node 3, otherwise country 1 would not threaten with the implementation of the BI-regime. As we know from Proposition 5, country 1 is always better off under full cooperation than under the PB-regime. Nevertheless, for convenience, this piece of information is repeated in condition i in Lemma 2 below.

Similarly, suppose the BI-threat has not been successful to establish cooperation and the game has proceeded to stage II . Country 1 will only use the BIE-threat if it is better off under full cooperation than under the BI-regime. That is, country 1's welfare must be higher at node 6 than at node 5. This is condition ii in Lemma 2 below.

Moreover, suppose the game has proceeded to stage III. Then, country 1 should be better off under full cooperation than under the BIE-regime for the BF-threat to be credible. Hence, country 1's welfare at node 8 must be higher than at node 7. This is condition iii in Lemma 2 below.

Finally, should country 1 have not been successful in establishing cooperation with the BF-threat, it must be better off implementing any of the BCA-threats than under the PB-regime, which we know is true from Proposition 5. Again, this piece of information is repeated for convenience in condition v in Lemma 2. Thus, any of the BCA-threats is credible - country 1 prefers any of the BCA-measures over being stuck in the non-cooperative PB-regime.

Lemma 2. The Credibility of BCA-threats by Country 1

i. Credibility of BI-threat: country 1 is better off under full cooperation than under the PB-regime.

ii. Credibility of BIE-threat: country 1 is better off under full cooperation than under the BI-regime if $\beta \leq \overline{\beta_1}(\gamma)$.

iii. Credibility of BF-threat: country 1 is better off under full cooperation than under the BIE-regime if $\beta \leq \overline{\beta_2}(\gamma)$.

iv. We have: $\overline{\beta_1}(\gamma) > \overline{\beta_2}(\gamma)$.

v. Country 1 is better off under all three BCA-regimes than under the PB-regime.

Proof. See Appendix B.2 and Proposition 5. □

A further conclusion which emerges from Lemma 2 is that full cooperation is particularly attractive to country 1 compared to imposing a unilateral BCA-regime if the damage evaluation parameter d is high compared to the evaluation parameter of the the net benefits from production and consumption A, i.e. if β is sufficiently small. Even if equipped with the strategic advantage of export rebates in addition to import tariffs, country 1 prefers full cooperation over unilateral trade measures if global cooperation would generate large gains from cooperation, i.e., if β is sufficiently small. This preference is of course based on selfish motives as the two thresholds $\overline{\beta_1}(\gamma)$ and $\overline{\beta_2}(\gamma)$ increase in γ.

Finally, we need to combine Lemma 1 and 2 in order to determine the equilibrium path. The logic can be illustrated by considering for instance stage III in Figure 2. We note from Lemma 1 that we only proceeded to stage III if $\beta < \underline{\beta_2}(\gamma)$. That is, previous attempts to enforce cooperation have failed. Suppose, the BF-threat is successful in establishing cooperation in stage III, i.e., $\beta \geq \underline{\beta_3}(\gamma)$. Hence, together, we have $\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$. From Lemma 2, condition iii, we know that the credibility of the BF-threat requires $\beta \leq \overline{\beta_2}(\gamma)$. Therefore, we have to test whether both inequalities ($\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$ and $\beta \leq \overline{\beta_2}(\gamma)$) can be satisfied such that cooperation is an equilibrium path and the game terminates at node 8. That is, if the enforcement condition in Lemma 1 for stage III holds, the corresponding credibility condition in Lemma 2 in stage III holds as well. Technically, this is done by showing that $\underline{\beta_2}(\gamma) < \overline{\beta_2}(\gamma)$. The same procedure is applied to stages I and II with similar conclusions which are summarised in Proposition 6.

Proposition 6. Subgame-Perfect Nash Equilibrium in the Escalating Penalty Game

1) Cooperative Region

- *If $\beta \geq \underline{\beta_1}(\gamma)$: full cooperation is achieved along the path: Cooperation→No Cooperation→BI→Cooperation. The game ends at node 4 in stage I in Figure 2.*
- *If $\underline{\beta_1}(\gamma) > \beta \geq \underline{\beta_2}(\gamma)$: full cooperation is achieved along the path: Cooperation → No Cooperation → BI →No Cooperation →BIE → Cooperation. The game ends at node 6 in stage II in Figure 2.*
- *If $\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$: full cooperation is achieved along the path: Cooperation→ No Cooperation → BI →No Cooperation→BIE →No Cooperation→BF→Cooperation. The game ends at node 8 in stage III in Figure 2.*

2) Non-cooperative Region

- *If $\underline{\beta_3}(\gamma) > \beta$, either the BF-regime is implemented following the BF-threat and the game ends at node 9 in stage III or if country 1 implements its most preferred BCA regime, then either (a) or (b):*

  (a) If $\underline{\beta_3}(\gamma) > \beta > 2\gamma$, there is no cooperation and the BIE-regime is implemented with an export rebate, which is not a full rebate ($\varphi^* < 1$). The equilibrium path is Cooperation→No Cooperation→BI→No Cooperation→BIE. The game ends at node 7 in stage II in Figure 2.

(b) If $2\gamma \geq \beta$, there is no cooperation and the BI-regime is implemented. The equilibrium path is Cooperation→No Cooperation→BI. The game ends at node 5 in stage I in Figure 2.

Proof. See Appendix B.3. □

In the cooperative region, full cooperation is established based on the threat by country 1 to impose BCA-measures. Hence, there are three paths to reach full cooperation. If $\beta \geq \underline{\beta_1}(\gamma)$, country 2 cooperates as a reaction to the BI-threat. If $\underline{\beta_1}(\gamma) > \beta \geq \underline{\beta_2}(\gamma)$, the BIE-threat works and if $\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$ only the BF-threat works. Since the potential gains from cooperation decrease in β, as we know from Proposition 5, this implies that if the potential gains from cooperation would be really large, only harsh punishment works if at all, but fails for $\underline{\beta_3}(\gamma) > \beta$.

In the non-cooperative region, i.e., $\underline{\beta_3}(\gamma) > \beta$, none of the threats are successful to enforce full cooperation, even though one can show that in these parameter range country 1 would be better off under full cooperation than under any of the BCA-regimes. Now there are basically two possible predictions how the game terminates.

One prediction results from the assumption that country 1 must commit to its threat provided country 2 does not accept cooperation. Accordingly, the BF-regime is implemented.

The other prediction results from the assumption that if country 1 cannot implement cooperation even with the harshest punishment, then it will implement its most preferred BCA-measure. That is, either the BI- or BIE-regime is implemented; the BF-regime is never chosen. The reason is that if implemented, country always prefer the BIE- over the BF-regime because under the former regime the export rebate rate is chosen optimally whereas under the latter regime but it is fixed. The non-cooperative parameter space can be divided into two sub-regions, in one in which the BIE-regime and another in which the BI-regime is implemented.

It appears to us that the second prediction is more convincing, as strictly speaking, we assume a game with full information. Hence, we would argue that country 1 can anticipate the failure to establish cooperation for $\underline{\beta_3}(\gamma) > \beta$ and hence will not proceed to stage II if $2\gamma \geq \beta$, and will proceed to stage II but not to stage III if $\underline{\beta_3}(\gamma) > \beta > 2\gamma$. This implies that the BF-regime only serves as a threat if cooperation can be established.

In any case, it is helpful to recall from Lemma 2 that all three BCA-regimes are preferred to the PB-regime by country 1. That is, also in this sense, the implementation of BCA-regimes is a credible threat.

5.3 Welfare Analysis of Equilibria

In this subsection, we evaluate our results from a normative perspective. We showed in Proposition 5 that BCAs, under some conditions, would cause a global welfare loss compared to the non-cooperative PB-regime. Hence, it is important to understand whether the implementation of the BCAs threats if they were not successful as threat to establish cooperation would cause a global welfare loss compared to the PB-regime.

Corollary 1. *Compared to the PB-regime, if BCAs are associated with a global welfare loss, they are only used as threats and are not implemented (cooperative region), while if they are implemented, they improve global welfare (non-cooperative region).*

Proof. Follows from comparing the threshold levels for which BCAs lead to a global welfare loss in Proposition 5 with the threshold levels for which full cooperation is achieved in Proposition 6 where $\underline{\beta}_W^{BF} > \underline{\beta_1} \, \forall \gamma$. □

Thus, the negative impact of BCA-measures on global welfare is avoided due to its strategic role to enforce cooperation. If they need to be implemented, they lead to higher global welfare. That is, all parameter values for which BCAs lead to a global welfare loss fall in the cooperative region. Moreover, it is also worthwhile to recall that country 1 has no incentive to implement BCA-measures along any equilibrium path in the cooperative region because cooperation is preferred to BCA-measures.

Another observation which we made above in Proposition 5 was that the potential gains from cooperation, $\Delta W = W^{FC*} - W^{PB*}$, are large if β is small. From Proposition 6 we know that if β is sufficiently small, i.e., $\underline{\beta_3}(\gamma) > \beta$, none of the BCA-regimes enforce cooperation. Combining both results, we ask the question to which extent do BCAs when implemented in the non-cooperative region close the gap ΔW. In order to answer this question, we employ a relative measure called the closing the gap index (CGI) as suggested by Eyckmans and Finus (2006).

$$CGI_W^{BI} = \frac{W^{BI*} - W^{PB*}}{\Delta W} \; \& \; CGI_W^{BIE} = \frac{W^{BIE*} - W^{PB*}}{\Delta W}$$
$$CGI_W^{BF} = \frac{W^{BF*} - W^{PB*}}{\Delta W} \tag{10}$$

Corollary 2. BCAs and the Global Welfare Gap

i. If the potential global gains from cooperation are sufficiently large, BCA-measures are not effective in establishing full cooperation.

ii. In the non-cooperative region, if BCAs are implemented, CGI_W^{BI} , CGI_W^{BIE} and CGI_W^{BF} are decreasing when lowering β whereas the global welfare gap ΔW is increasing.

Proof. Follows from Propositions 5 and 6 and Appendix B.5. □

On the one hand, BCAs close the global welfare gap fully through their strategic role for all $\beta \geq \underline{\beta_3}$, i.e., in the cooperative region. However, if β is sufficiently small, $\beta < \underline{\beta_3}$, full cooperation cannot be achieved. On the other hand, the lower β, the larger would be the global gains from full cooperation. Hence, whenever cooperation would be needed most, BCAs do not enforce cooperation. Moreover, the larger the potential gains from cooperation, the smaller the success of BCAs if they are implemented. As indicated above, this result has some resemblance with 'the paradox of cooperation', a term coined by Barrett (1994) in his seminal paper.[13]

[13] Barrett (1994) proposed this term in an environmental agreement game without trade. In his context, either only small agreements are stable or if large agreements are stable, then the global gains from cooperation are small.

5.4 Alternative Assumptions

We have put forward two main arguments to motivate the sequential escalating penalty game. First, the distortionary global welfare effects of BCAs increases along the latter of escalation. Therefore, escalation should only be used if needed. Second, country 1 prefers cooperation over the implementation of BCAs when escalation is needed, i.e. when country 2 does not accept cooperation. Nevertheless, one may wonder about the outcome of an alternative penalty game with only one stage. That is, country 1 moves first and proposes cooperation, choosing among the three BCA-threats right from the beginning to enforce cooperation. As discussed in Appendix B.4, we find that full cooperation is the unique subgame-perfect Nash equilibrium following a BF-threat if $\underline{\beta_2}(\gamma) > \beta \geq \beta_3(\gamma)$. Also for $\beta < \underline{\beta_3}$, the equilibrium with no cooperation is unique. If $\underline{\beta_3} > \beta > 2\gamma$, the BIE-regime is implemented, whereas if $2\gamma \geq \beta$, the BI-regime is implemented. This is in line with the results of the escalating penalty game as stated in Proposition 6.

However, if $\beta_1(\gamma) > \beta \geq \beta_2(\gamma)$, we have no longer one but two subgame-perfect equilibria, one following a BIE- and the other a BF-threat and for $\beta \geq \beta_1(\gamma)$, we have no longer one but three subgame-perfect equilibria, following a BI-, BIE- and BF-threat. Therefore, our sequential escalating penalty game in Figure 2 has the advantage over a game of a simultaneous choice of BCA-threats in that it always delivers a unique equilibrium for each parameter range. It is easily confirmed that all qualitative conclusions regarding global welfare in the different equilibria derived in subsection 5.3 still hold. That is, in the non-cooperative region in which BCAs are implemented, BCAs are globally welfare improving compared to the PB-regime, but, unfortunately, the gap between full cooperation and the non-cooperative equilibria is only closed to a small extent.

Another issue is related to the credibility of threats. One may argue that in the cooperative parameter range $\beta \geq \beta_1(\gamma)$ for which it is sufficient to establish cooperation using the BI-threat, country 1 would most likely use the harsher BIE-threat instead. The reason is that the BIE-threat also establishes cooperation, but, country 1's welfare would be higher if the threat would need to be implemented in this parameter range (see Appendix B.4). Taking this issue into consideration, in Proposition 6, the BI-threat would need to be replaced by the BIE-threat in the first equilibrium in the cooperative region. However, in the second and third equilibrium in the cooperative region, and the non-cooperative parameter region, nothing would change. Therefore, again, all qualitative welfare conclusions derived in the subsection 5.3 would still hold.

6 Conclusions

The absence of a global agreement to mitigate climate change raises concerns about carbon leakage, which undermines the effectiveness of unilateral actions. Economists and policy makers have suggested border carbon adjustments (BCAs) as a measure to address carbon leakage but also to enforce cooperative climate agreements. To this end, we assessed the effectiveness of three forms of BCAs in an intra-industry trade model with two countries, which differ in their perception of environmental damages and which choose their carbon taxes strategically. Our game comprises three stages: countries play an offer/threat response bargaining game in stage 1, choose their carbon taxes in stage 2 and firms choose their output in stage 3.

We started from a non-cooperative situation of mutual production-based taxes, which we called the PB-regime. Country 1, which is more concerned about environmental damages would like to move to a cooperative situation of socially optimal taxes with lower global emissions and higher global welfare, but country 2 not: it perceives the benefits from reduced damages and additional tax revenues to be smaller than the loss of producer and consumer surplus. We then analysed whether and under which conditions country 1 can enforce cooperation through threats, which constituted a sequence of escalating penalties. We tested the credibility of threats by deriving the subgame-perfect equilibrium path along a sequential offer/threat (country 1) and response (country 2) game. Threats constituted various forms of BCAs.

We considered three designs of BCAs. a) BCAs on imports, implying that country 1 imposes unilaterally a tariff on imports from country 2, where this tariff fully adjusts the difference between the carbon taxes in the two countries (BI-regime). b) BCAs on imports are complemented by country 1 giving rebates to its firm on its exports to country 2 where the rebate rate is chosen optimally (BIE-regime). c) The same as b, though the export rebate is not chosen optimally but is a full rebate, which de facto means that country 1 imposes a unilateral consumption-based tax (BF-regime).

We showed that import tariffs and export rebates protect the competitiveness of country 1's firm in the home and the foreign market, respectively. Country 1 can better control global emissions through BCAs as leakage effects are lower. Moreover, country 1 benefits from tariff revenues as they essentially shift tax revenues from country 2 to country 1. However, we also showed that tariffs disadvantage consumers in country 1 and export rebates are costly. This explained among other factors why country 1 may not choose a full rebate, provided it can choose its rebate optimally. It also explained that if BCAs are successful in enforcing full cooperation, country 1 has no incentive to implement BCAs. If BCAs-threats do not work, then country 1 will be better off with implementation BCAs than being stuck in the PB-regime. Under those conditions global emissions will be lower and global welfare higher than in the PB-regime. In its own interest, country 1 will not implement the most distortinary BCA-regime (and most harmful BCA-regime for country 2), which we showed is the BF-regime, but either the BI- or the BIE-regime. Thus, it emerged from our paper that unilateral BCA measures are helpful in either fully internalizing a global externality by enforcing full cooperation or at least partially internalizing a global externality if they need to be implemented.

Nevertheless, our results also have some resemblance with Barrett's paradox of cooperation (Barrett, 1994). The higher environmental damages are compared to the net benefits from production and consumption, the larger are the potential gains from cooperation, but the harsher must be the threat of punishment in order to enforce cooperation. In particular, when those gains from cooperation are really large, even the harshest punishment is not sufficient to establish cooperation.

In this paper, we considered one aspect of asymmetry among countries, which was the evaluation of environmental damages. One could also look at other aspects, as for instance different carbon intensities across countries (Böhringer et al., 2014; Fischer and Fox, 2012). Another possible extension could be to extend the n-player symmetric agreement formation game considered in Helm and Schmidt (2015) and Al Khourdajie and Finus (2020) to asymmetry. Finally, one could analyse possible transfer mechanisms between the two heterogeneous countries along the lines of optimal transfers by Finus and McGinty (2019) considering also trade and BCAs in these models.

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Appendix

A Appendix of Section 4

In the third stage, the output stage, using (2) and (3) in the text, delivers $\frac{\partial^2 \pi_k}{\partial x_{ki}^2} = -2 < \frac{\partial^2 \pi_k}{\partial x_{ki} \partial x_{\ell i}} = -1 < 0$, which guarantees a unique Nash equilibrium in each market (Eichberger, 1993; Friedman, 1986). That is, $\left(\frac{\partial^2 \pi_k}{\partial x_{ki}^2} \frac{\partial^2 \pi_\ell}{\partial x_{\ell i}^2}\right) - \left(\frac{\partial^2 \pi_k}{\partial x_{ki} \partial x_{\ell i}} \frac{\partial^2 \pi_\ell}{\partial x_{\ell i} \partial x_{ki}}\right) = 3 > 0$ $\forall\, k \neq \ell$.

The welfare functions in (7) and (8) in the text can be written explicitly as follows:

$$\begin{aligned} W_1 = {} & \underbrace{\frac{(x_{11}+x_{21})^2}{2}}_{CS_1} + \underbrace{(x_{11})^2 + (x_{12})^2}_{PS_1} + \underbrace{t_1(x_{11}+x_{12})}_{TR_1} - \underbrace{\gamma de}_{D_1} \\ & + \underbrace{(t_1 - t_2)x_{21}}_{BCAI_1} - \underbrace{\varphi t_1 x_{12}}_{BCAE_1} \end{aligned} \tag{A.1}$$

$$W_2 = \underbrace{\frac{(x_{22}+x_{12})^2}{2}}_{CS_2} + \underbrace{(x_{22})^2 + (x_{21})^2}_{PS_2} + \underbrace{t_2(x_{22}+x_{21})}_{TR_2} - \underbrace{(1-\gamma)\, de}_{D_2} \tag{A.2}$$

We define $\beta := \frac{A}{d}$. We recall that $A := a - c$ is a proxy for the market size or the net benefits of production and consumption, d is the global damage parameter and γ the share parameter of global damages.

Due to lack of space, the subsequent proofs are a sketch; detailed computations are available from the authors upon request.

A.1 FC-Regime

Inserting uniform taxes $t_{1i} = t_{2i} = t$ for $i = 1, 2$ into (4) in the text, gives equilibrium outputs $x_{ki}^{FC} = \frac{A-t}{3}$ $\forall\, i = 1, 2$ and $k = 1, 2$. Inserting equilibrium outputs into the aggregate welfare function $W^{FC} = W_1^{FC} + W_2^{FC}$, differentiating with respect to t, yields the following first- and second order conditions:
$\frac{\partial W^{FC}}{\partial t} = -\frac{4}{9}(A + 2t) + \frac{4}{3}d = 0$ and $\frac{\partial^2 W}{\partial t^2} = -\frac{8}{9} < 0$. Solving for the socially optimal carbon tax, leads to:

$$t^{FC*} = -\frac{1}{2}A + \frac{3}{2}d\,. \tag{A.3}$$

Hence, we have $x_{ki}^{FC*} = (A-d)/2$, $e^{FC*} = 2\,(A-d)$, $W_1^{FC*} = \frac{(A-d)(A+d-4\gamma d)}{2}$, $W_2^{FC*} = \frac{(A-d)(A-3d+4\gamma d)}{2}$ and $W^{FC*} = (A-d)^2$. In order to have positive production levels (i.e., interior solutions), we impose the non-negativity constraint (NN-constraint) $A > d$ or, using $\beta := \frac{A}{d}$, $\beta > 1$.

Note that this constraint as well as those required under the other regimes are summarised in Table A.1 in Appendix A.6.

A.2 PB-Regime

Inserting effective taxes in Table 1 into (4) in the text, leads to $x_{11}^{PB} = x_{12}^{PB} = \frac{A-2t_1+t_2}{3}$ and $x_{22}^{PB} = x_{21}^{PB} = \frac{A-2t_2+t_1}{3}$. Inserting these outputs into (A.1) and (A.2) and setting $BCAI_1 = BCAE_1 = 0$, give the following first-order conditions:

$\frac{\partial W_1^{PB}}{\partial t_1} = -\frac{1}{9}(4A + 7t_1 + t_2) + \frac{2}{3}\gamma d = 0$ and
$\frac{\partial W_2^{PB}}{\partial t_2} = -\frac{1}{9}(4A + 7t_2 + t_1) + \frac{2}{3}(1-\gamma) d = 0.$

Solving $\frac{\partial W_1^{PB}}{\partial t_1} = 0$ and $\frac{\partial W_2^{PB}}{\partial t_2} = 0$ simultaneously, gives equilibrium taxes:

$$t_1^{PB*} = d\left(\gamma - \frac{1}{8}\right) - \frac{1}{2}A, \tag{A.4}$$

$$t_2^{PB*} = d\left(\frac{7}{8} - \gamma\right) - \frac{1}{2}A\,, \tag{A.5}$$

where the second order conditions are satisfied because $\frac{\partial^2 W_i}{\partial {t_i}^2} = -\frac{7}{9} < 0$, $\frac{\partial^2 W_i}{\partial t_i \partial t_j} = -\frac{1}{9} < 0$. Moreover, $\frac{\partial^2 W_i}{\partial {t_1}^2}\frac{\partial^2 W_2}{\partial {t_2}^2} - \frac{\partial^2 W_1}{\partial t_1 \partial t_2}\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = \frac{16}{27} > 0$, which ensures a unique Nash equilibrium. These conditions are are also sufficient for the Routh-Hurwitz stability condition to be satisfied (Brander and Spencer, 1985). The slopes of the reaction functions are given by $\frac{\partial t_i(t_j)}{\partial t_j} = -\frac{\partial^2 W_i}{\partial t_i \partial t_j} / \frac{\partial^2 W_i}{\partial {t_i}^2} = -\frac{1}{7} < 0$. The reaction functions are given by $RF_1^{PB} := t_1(t_2) = -\frac{1}{7}(4A + t_2 - 6\gamma d)$ and $RF_2^{PB} := t_2(t_1) = -\frac{1}{7}(4A + t_1 - 6(1-\gamma)d)$.

Inserting equilibrium taxes into outputs, we obtain equilibrium outputs, equilibrium welfare levels W_1^{PB*} and W_2^{PB*} with $W^{PB*} = W_1^{PB*} + W_2^{PB*} = \frac{(4A-7d)(4A-d)}{16}$ and $e^{PB*} = 2A - \frac{1}{2}d$. From equilibrium outputs, the NN-constraint $\beta > \frac{1}{4}(8\gamma - 3)$ follows. Moreover, we always have $t_1^{PB*} > t_2^{PB*}$ for all $\gamma > \frac{1}{2}$.

A.3 BI-Regime

Inserting the effective taxes in Table 1 into (4) in the text, leads to $x_{11}^{BI} = x_{21}^{BI} = \frac{A-t_1}{3}$, $x_{12}^{BI} = \frac{A-2t_1+t_2}{3}$ and $x_{22}^{BI} = \frac{A-2t_2+t_1}{3}$. Inserting these outputs into (A.1) and (A.2) and setting $BCAE_1 = 0$, we obtain W_1^{BI} and W_2^{BI}. The first-order conditions are given by:

$\frac{\partial W_1^{BI}}{\partial t_1} = -\frac{1}{9}(A + 10t_1 - 2t_2) + \gamma d = 0$ and $\frac{\partial W_2^{BI}}{\partial t_2} = -\frac{1}{3}(t_1 + t_2) + \frac{1}{3}(1-\gamma)d = 0.$

Solving $\frac{\partial W_1^{BI}}{\partial t_1} = 0$ and $\frac{\partial W_2^{BI}}{\partial t_2} = 0$ simultaneously, gives equilibrium taxes:

$$t_1^{BI*} = \left(\frac{7}{12}\gamma + \frac{1}{6}\right)d - \frac{1}{12}A\,, \tag{A.6}$$

$$t_2^{BI*} = \left(\frac{5}{6} - \frac{19}{12}\gamma\right)d + \frac{1}{12}A\,, \tag{A.7}$$

where the second derivatives are given by $\frac{\partial^2 W_1}{\partial {t_1}^2} = -\frac{10}{9} < 0$, $\frac{\partial^2 W_1}{\partial t_1 \partial t_2} = \frac{2}{9} > 0$, $\frac{\partial^2 W_2}{\partial {t_2}^2} = -\frac{1}{3} < 0$ and $\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = -\frac{1}{3} < 0$. Therefore, we have $\frac{\partial^2 W_1}{\partial {t_1}^2}\frac{\partial^2 W_2}{\partial {t_2}^2} - \frac{\partial^2 W_1}{\partial t_1 \partial t_2}\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = \frac{4}{9} > 0$, which ensures a unique and stable equilibrium.

The slopes of the reaction functions of countries are given by $\frac{\partial t_1(t_2)}{\partial t_2} = -\frac{\partial^2 W_1}{\partial t_1 \partial t_2} / \frac{\partial^2 W_1}{\partial {t_1}^2} = \frac{1}{5} > 0$ and $\frac{\partial t_2(t_1)}{\partial t_1} = -\frac{\partial^2 W_2}{\partial t_2 \partial t_1} / \frac{\partial^2 W_2}{\partial {t_2}^2} = -1 < 0$ and the reaction functions by $RF_1^{BI} := t_1(t_2) = \frac{-A+9\gamma d}{10} + \frac{1}{5}t_2$ and $RF_2^{BI} := t_2(t_1) = (1-\gamma)d - t_1$.

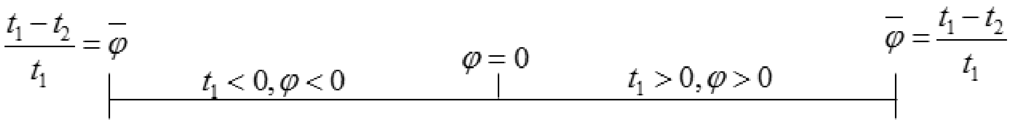
Inserting equilibrium taxes into outputs, it turns out that the most restrictive NN-constraint requires $\beta > \frac{1}{5}(11\gamma - 2)$ and equilibrium global emissions are given by $e^{BI*} = \frac{25A - d(\gamma-8)}{18}$.

Since the difference between the two equilibrium taxes is ambiguous, we need to impose a BCA-constraint such that $t_1^{BI*} > t_2^{BI*}$. The BCA-constraint requires $\beta < 13\gamma - 4$. Inserting t_1^{BI*} and t_2^{BI*} into welfare functions, gives W_1^{BI*}, W_2^{BI*} and $W^{BI*} = W_1^{BI*} + W_2^{BI*}$.

A.4 BIE-Regime

In models with imperfect competition, generally, equilibrium taxes can be positive or negative (in which case they are subsidies). Therefore, the feasible values of the rebate rate depends on the equilibrium taxes in country 1 and 2. Moreover, we need to consider $t_1 > t_2$ and $t_1(1-\varphi) \geq t_2$.

If $t_1 > 0, \varphi > 0$. We have $0 < \varphi \leq \overline{\varphi} = \frac{t_1 - t_2}{t_1}$ where for the maximum allowable rebate rate $\overline{\varphi}$, $\overline{\varphi} \leq 1$ holds if $t_1 > t_2 \geq 0$, while $\overline{\varphi} > 1$ if $t_2 < 0$. If $0 > t_1 > t_2$, then $\varphi < 0$. In such cases, the feasible values for φ is $0 > \varphi \geq \overline{\varphi} = \frac{t_1 - t_2}{t_1}$. This is illustrated below.



Inserting effective taxes in Table 1 into (4), gives equilibrium output levels $x_{11}^{BIE} = x_{21}^{BIE} = \frac{A - t_1}{3}$, $x_{12}^{BIE} = \frac{A - 2t_1(1-\varphi) + t_2}{3}$ and $x_{22}^{BIE} = \frac{A - 2t_2 + t_1(1-\varphi)}{3}$. Inserting these outputs into (A.1) and (A.2), gives the welfare function of each country under this regime.

The first-order conditions are given by:

$\frac{\partial W_1^{BIE}}{\partial t_1} = -\frac{1}{9}\left(A + 10t_1 + 4t_1\varphi^2 - 2t_2 - \varphi\left(A + 8t_1 + t_2 - 3\gamma d\right)\right) + \gamma d = 0\,,$

$\frac{\partial W_1^{BIE}}{\partial \varphi} = \frac{1}{9}t_1\left(A + 4t_1 - 4t_1\varphi + t_2 - 3\gamma d\right) = 0$ and

$\frac{\partial W_2^{BIE}}{\partial t_2} = -\frac{1}{3}\left(t_1 + t_2\right) + \frac{1}{3}(1-\gamma)d = 0$, with the last condition being the same as in the BI-regime.

Solving $\frac{\partial W_1^{BIE}}{\partial t_1} = 0$, $\frac{\partial W_2^{BIE}}{\partial t_2} = 0$ and $\frac{\partial W_1^{BIE}}{\partial \varphi} = 0$ simultaneously, the Nash equilibrium carbon taxes are given by:

$$t_1^{BIE*} = \frac{1}{3}d\left(\gamma + 1\right) > 0\,, \tag{A.8}$$

$$t_2^{BIE*} = \frac{2}{3}d\left(1 - 2\gamma\right) \leq 0\,, \tag{A.9}$$

and the optimal export rebate rate is given by:

$$\varphi^{*} = \frac{3\left(A + d\left(2 - 3\gamma\right)\right)}{4\, d\left(\gamma + 1\right)} > 0\,, \tag{A.10}$$

noting that $\varphi^{*} \leq (>)1$ if $\beta \leq (>)\ddot{\beta}(\gamma) = \frac{1}{3}\left(13\gamma - 2\right)$. We obtain the following second derivatives: $\frac{\partial^2 W_1}{\partial t_1{}^2} = -\frac{10}{9} - \frac{4\varphi}{9}(\varphi + 2) < 0\,\forall\,\varphi$, $\frac{\partial^2 W_1}{\partial t_1 \partial t_2} = \frac{2+\varphi}{9} > 0$ for all $\varphi \in (-2, \infty)$, $\frac{\partial^2 W_1}{\partial t_1 \partial t_2} = \frac{2+\varphi}{9} < 0$ for all $\varphi \in (-\infty, -2)$, $\frac{\partial^2 W_2}{\partial t_2{}^2} = -\frac{1}{3} < 0$, $\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = -\frac{1}{3} < 0$ and $\frac{\partial^2 W_1}{\partial \varphi^2} = -\frac{4}{9}t_1^2 < 0\,\forall\, t_1 \neq 0$. Hence, second order conditions hold and $\frac{\partial^2 W_1}{\partial t_1{}^2}\frac{\partial^2 W_2}{\partial t_2{}^2} - \frac{\partial^2 W_1}{\partial t_1 \partial t_2}\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = \frac{4}{9} + \frac{\varphi(4\varphi-7)}{27} > 0\,\forall\varphi$ guarantees uniqueness.

The slopes of the reaction functions are given by $\frac{\partial t_1(t_2)}{\partial t_2} = \frac{\varphi+2}{2(2\varphi^2-4\varphi+5)} > 0\,\forall\;\varphi > 0$ and $\frac{\partial t_2(t_1)}{\partial t_1} = -1 < 0$. The reaction functions are given by $RF_1^{BIE} := t_1(t_2) = \frac{t_2(\varphi+2)-A+9\gamma d+\varphi(A-3\gamma d)}{2(2\varphi^2-4\varphi+5)}$ and $RF_2^{BIE} := t_2(t_1) = (1-\gamma)d - t_1$.

Inserting equilibrium taxes into outputs, it turns out that the most restrictive NN-constraint requires $\beta > \frac{1}{3}\left(7\gamma - 2\right)$. Equilibrium global emissions are $e^{BIE*} = \frac{51A-d(5\gamma-14)}{36}$. We also need to impose a BCA-constraint such that $t_1^{BIE*}(1-\varphi^{*}) \geq t_2^{BIE*}$, which leads to $\beta \leq \frac{1}{3}\left(29\gamma - 10\right)$. Note that $t_1^{BIE*} > t_2^{BIE*}$ always holds. Inserting t_1^{BIE*} and t_2^{BIE*} into welfare functions, we obtain W_1^{*BIE} , W_2^{*BIE} and $W^{*BIE} = W_1^{*BIE} + W_2^{*BIE}$.

A.5 BF-Regime

Inserting the effective taxes in Table 1 into (4) in the text, gives equilibrium output: $x_{11}^{BF} = x_{21}^{BF} = \frac{A-t_1}{3}$, $x_{12}^{BF} = \frac{A+t_2}{3}$ and $x_{22}^{BF} = \frac{A-2t_2}{3}$. Inserting these outputs into (A.1) and (A.2), gives the welfare function of each country. The first-order conditions are given by

$\frac{\partial W_1^{BF}}{\partial t_1} = \frac{1}{3}\left(t_2 - 2t_1 + 2\gamma d\right) = 0$ and $\frac{\partial W_2^{BF}}{\partial t_2} = -\frac{1}{3}\left(t_1 + t_2\right) + \frac{1}{3}(1-\gamma)d = 0$.

Solving $\frac{\partial W_1^{BF}}{\partial t_1} = 0$ and $\frac{\partial W_2^{BF}}{\partial t_2} = 0$ simultaneously, the equilibrium carbon taxes are given by:

$$t_1^{BF*} = \frac{1}{3}d\left(\gamma + 1\right) > 0\,, \tag{A.11}$$

$$t_2^{BF*} = \frac{2}{3}d\left(1 - 2\gamma\right) \leq 0\,, \tag{A.12}$$

with $\frac{\partial^2 W_1}{\partial t_1{}^2} = -\frac{2}{3} < 0$, $\frac{\partial^2 W_1}{\partial t_1 \partial t_2} = \frac{1}{3} > 0$, and $\frac{\partial^2 W_2}{\partial t_2{}^2} = -\frac{1}{3} < 0$, $\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = -\frac{1}{3} < 0$ where $\frac{\partial^2 W_1}{\partial t_1{}^2}\frac{\partial^2 W_2}{\partial t_2{}^2} - \frac{\partial^2 W_1}{\partial t_1 \partial t_2}\frac{\partial^2 W_2}{\partial t_2 \partial t_1} = \frac{1}{3} > 0$. The slopes of the reaction function are given by $\frac{\partial t_1(t_2)}{\partial t_2} = \frac{1}{2} > 0$ and $\frac{\partial t_2(t_1)}{\partial t_1} = -1 < 0$ and the reaction functions are given by $RF_1^{BF} := t_1(t_2) = \frac{1}{2}t_2 + \gamma d$ and $RF_2^{BF} := t_2(t_1) = (1-\gamma)d - t_1$.

Inserting equilibrium taxes into outputs, the most restrictive NN-constraint requires $\beta > \frac{1}{3}\left(\gamma + 1\right)$. Global emissions are given by $e^{BF*} = \frac{12A+2d(\gamma-2)}{9}$.

There is no need to impose a BCA-constraint as we always have $t_1^{BF*} > t_2^{BF*}$ and $t_1^{BF*}(1-\varphi) = 0 \geq t_2^{BF*}$ with equality if and only if $\gamma = 0.5$.

Inserting equilibrium taxes into welfare functions, gives W_1^{BF*} and W_2^{BF*} and $W^{BF*} = W_1^{BF*} + W_2^{BF*}$.

A.6 All Regimes

We summarise the conditions that satisfy the NN-constraint and the BCA-constraint under various regimes in the following table. For comparisons across regimes, we use the most restrictive condition, which is summarised under "Feasible Range".

Table A.1: Feasible Range of Parameters Values

Regime/Constraint	NN-constraint	BCA-constraint
FC	$\beta > 1$	/
PB	$\beta > \frac{1}{4}(8\gamma - 3)$	/
BI	$\beta > \frac{1}{5}(11\gamma - 2)$	$\beta < 13\gamma - 4$
BIE	$\beta > \frac{1}{3}(7\gamma - 2)$	$\beta \leq \frac{1}{3}(29\gamma - 10)$
BF	$\beta > \frac{1}{3}(\gamma + 1)$	/
Feasible Range	$\beta > \check{\beta} = 1$ for all $\gamma < 0.6363$ $\beta > \check{\beta} = \frac{1}{5}(11\gamma - 2)$ for all $\gamma > 0.6363$	$\beta \leq \hat{\beta} = \frac{1}{3}(29\gamma - 10)$

A.7 Reaction Functions

As shown in Figure 1 (b) and (c), the reaction functions of both countries under the BCA-regimes are piecewise. For instance, in Figure 1 panel (b), $RF_1^{BI} := t_1(t_2)$, which is given in Appendix A.3, intersects with the 45°-line at $\bar{t_2} = \frac{1}{8}(9\gamma d - A)$. At this tax level, matching taxes $t_1(\bar{t_2}) = \bar{t_2}$ is a best response of country 1. For any tax level $t_2 \geq \bar{t_2}$, the reaction function jumps to $RF_1^{PB} := t_1(t_2)$, given in Appendix A.2. Similarly for country 2, $RF_2^{BI} := t_2(t_1)$ intersects with the 45°-line at $\bar{t_1} = \frac{1}{2}d(1-\gamma)$. For any tax level $t_1 \leq \bar{t_1}$, country 2's reaction function jumps to $RF_2^{PB} := t_2(t_1)$. Taken together, the constraint needed for $t_2 < \bar{t_2}$ and $t_1 > \bar{t_1}$ is the BCA-constraint stated in Appendix A.3. There are generally two possibilities for the reaction functions to intersect above the 45°-line: the intersection of the RFs under the PB-regime and the intersection of the RFs under the BI-regime. The first possibility is not possible for all $\gamma \geq 0.5$, which we assume in our model, while the second possibility is ruled out by the BCA-constraint. Hence, the unique solution is the intersection of the RFs under the BI-regime below the 45°-line.

A similar analysis applies to Figure 1 panel (c). As shown above, the RF_2 under the three BCA-regimes is the same. Hence, we have the same intersection points with the 45°-line as above. For country 1, the reaction function RF_1^{BIE} and RF_1^{BF}, which are given in Appendices A.4 and A.5, respectively, intersects with the 45°-line at $\bar{t_2} = \frac{\varphi(A-3\gamma d)+9\gamma d-A}{4\varphi^2-9\varphi+8}$ under the BIE-regime and at $\bar{t_2} = 2\gamma d$ under the BF-regime. For any $t_2 \geq \bar{t_2}$, the reaction function of country 1 jumps to the PB-regime.

It is clear from the previous appendices that country 2's reaction function is always downward sloping and this is also true for country 1's reaction function under the PB-regime. For all BCA-regimes, the reaction function of country 1 is upward sloping.

A.8 Proof of Proposition 3

i, ii. The ranking of equilibrium tax levels follows directly from comparing the taxes provided in (A.3) to (A.12), using the NN-and BCA-constraints in the feasible range in Table A.1, i.e. $\check{\beta} < \beta \leq \hat{\beta}$.

iii. Follows from Appendix A.4, in particular (A.10), where $\ddot{\beta}(\gamma) = \frac{1}{3}(13\gamma - 2)$.

iv. From Appendix A.4, we have $t_1^{BIE*} > 0$ and $\varphi^* > 0$. Thus, the effective tax of country 1 in market 2, t_{12}^{BIE*}, is given by $t_{12}^{BIE*} = t_1^{BIE*}(1 - \varphi^*) = \frac{d(13\gamma-2)-3A}{12}$. Comparing t_{12}^{BIE*} with t_{12}^{PB*} (which is t_1^{PB*}in (A.4)) and t_{12}^{BI*} (which is t_1^{BI*} in (A.6)), we find that $t_{12}^{BI*} > t_{12}^{BIE*}$ and $t_{12}^{BIE*} > t_{12}^{PB*}$ always hold as long as the NN-constraints hold. Hence, a) $t_{12}^{PB*} < t_{12}^{BIE*} < t_{12}^{BI*}$. Under the BF-regime, $t_{12}^{BF*} = 0$ by assumption. We also have $t_{12}^{BI*} > 0$ as long as $\check{\beta} < \beta \leq \hat{\beta}$. Therefore, b) $t_{12}^{BF*} < t_{12}^{BI*}$. Whether t_{12} is larger under the BIE- than under the BF-regime depends on the value of the equilibrium export rebate rate. Thus, we have c) $t_{12}^{BF*} \leq (>)\, t_{12}^{BIE*}$ if $\varphi^* \leq (>)1$, where $t_{12}^{BF*} = 0$. Finally, we could have $t_{12}^{BF*} \leq t_{12}^{PB*}$ if $\beta \leq 2\gamma - \frac{1}{4}d$. However, this condition violates the NN-constraint $\beta > \check{\beta} = 1$ for all $\gamma \leq 0.625$ and violates the NN-constraint $\beta > \check{\beta} = \frac{1}{5}(11\gamma - 2)$ for all $\gamma \geq 0.75$. Therefore, if $\beta \leq 2\gamma - \frac{1}{4}d$ for all $0.625 < \gamma < 0.75$, we have $t_{12}^{BF*} \leq t_{12}^{PB*}$, while if $\gamma \leq 0.625$ or $\gamma \geq 0.75$ and if $\beta > 2\gamma - \frac{1}{4}d$ for all γ, we have $t_{12}^{BF*} > t_{12}^{PB*}$. Hence, d) $t_{12}^{BF*} \leq (>) t_{12}^{PB*}$.

vi. From (A.3), (A.4) and (A.5), we find that $t_1^{PB*} < t^{FC*}$ for all $\gamma < 1.625$, which holds, given $\gamma \leq 1$, and $t_2^{PB*} < t^{FC*}$ for all d and γ. We have shown in point i that t_1^{BI*} is the lowest tax level across the BCA-regimes in country 1. Thus, we compare t_1^{BI*} with t^{FC*} and find that $t_1^{BI*} \geq t^{FC*}$ if $\beta \geq \frac{16-7\gamma}{5}$ for all $\gamma \geq 0.59$, given our feasible constraints, $\check{\beta} < \beta \leq \hat{\beta}$. Even for country 2, we find that the lowest tax level across the BCA-regimes, t_2^{BIE*} (or t_2^{BF*}) could be higher than the socially optimal tax level, $t_2^{BIE*}(t_2^{BF*}) \geq t^{FC*}$ if $\beta \geq \frac{5+8\gamma}{3}$ for all $\gamma \gtrsim 0.7$, given our feasible constraints, $\check{\beta} < \beta \leq \hat{\beta}$.

A.9 Proof of Proposition 4

We compare global emission levels which are given in Appendices A.2 to A.5. We use the NN- and BCA-constraints in the "Feasible Range" listed in Table A.1 above.

- Comparison with the PB-regime:

  $e^{PB*} < e^{BI*}$ if $\beta < \frac{1}{11}(1-\gamma)$, $e^{PB*} < e^{BIE*}$ if $\beta < \frac{1}{21}(4 - 5\gamma)$, and $e^{PB*} < e^{BF*}$ if $\beta < \frac{1}{3}\left(\gamma + \frac{1}{4}\right)$, where all the above conditions can be shown to violate the NN-constraints. Hence, we have $e^{BI*}, e^{BIE*}, e^{BF*} < e^{PB*}$.

- Comparison across the BCA-regimes:

  $e^{BIE*} \leq e^{BI*}$ if $\beta \leq 3\gamma - 2$, which violates the NN-constraints. Thus, we have $e^{BIE*} > e^{BI*}$.

  $e^{BF*} \leq e^{BI*}$ if $\beta \geq 5\gamma$, which violates the BCA-constraint only if $\gamma < 0.714$. Note that if $\beta \geq 5\gamma$, this implies that $\varphi^* > 1$ and therefore $e^{BF*} \leq e^{BIE*}$. Thus, if $\beta < 5\gamma$, $e^{BF*} > e^{BI*}$ is possible.

$e^{BIE*} \leq (>) e^{BF*}$ if $\beta \leq (>) \ddot{\beta}(\gamma) = \frac{1}{3}(13\gamma - 2)$, i.e., if the optimal rebate is less than or equal (larger than) a full rebate, i.e., $\varphi^* \leq (>) 1$.

A.10 Proof of Proposition 5

Using Appendices from A.1 to A.5, and upon substitution of equilibrium taxes and outputs in country's welfare function, equilibrium welfare is obtained.

1) The global welfare gap between the FC- and the PB-regime is $\Delta W = W^{FC*} - W^{PB*} = \frac{9}{16}d^2$. $W_1^{FC*} > W_1^{PB*}$ for all $\gamma \geq 0.5$ but $W_2^{FC*} \geq (<) W_2^{PB*}$ if $\gamma \leq (>) \overline{\gamma} = \frac{41}{64} \backsimeq 0.64$.

2) Comparison BCA-regimes vs PB-regime

- $W^{BI*} \leq W^{PB*}$ if $\beta \geq$ (or $\leq$) $\frac{1}{61}(\gamma + 152) + (-)\frac{9}{122}\sqrt{1034 - 256\gamma(\gamma - 1)}$. The first condition violates the BCA-constraint for all $\gamma \leq 0.853$, while the second condition violates the NN-constraints. Therefore, $W^{BI*} > W^{PB*}$ except if $\beta > \underline{\beta}_W(BI) = \frac{1}{61}(\gamma + 152) + \sqrt{1034 - 256\gamma(\gamma - 1)}$ for all $\gamma > \underline{\gamma}_1 = 0.853$.

- $W^{BIE*} \leq W^{PB*}$ if $\beta \geq$ (or $\leq$) $\frac{1}{75}(202 - 23\gamma) + (-)\frac{3}{25}\sqrt{434 - 16\gamma(2 + \gamma)}$. The first condition violates the BCA-constraint for all $\gamma \leq 0.843$, while the second condition is not feasible. Therefore, $W^{BIE*} > W^{PB*}$ except if $\beta > \underline{\beta}_W(BIE) = \frac{1}{75}(202 - 23\gamma) + \frac{3}{25}\sqrt{434 - 16\gamma(2 + \gamma)}$ for all $\gamma > \underline{\gamma}_2 = 0.843$.

- $W^{BF*} \leq W^{PB*}$ if $\beta \geq$ (or $\leq$) $\frac{1}{3}(\gamma + 7) + (-)\frac{1}{4}\sqrt{81 - 16\gamma^2}$. The first condition violates the BCA-constraint for all $\gamma \leq 0.83$, while the second condition violates the NN-constraints. Therefore, $W^{BF*} > W^{PB*}$ except if $\beta > \underline{\beta}_W(BF) = \frac{1}{3}(\gamma + 7) + \frac{1}{4}\sqrt{81 - 16\gamma^2}$ for all $\gamma > \underline{\gamma}_3 = 0.83$.

  We also have $\underline{\beta}_W(BI) > \underline{\beta}_W(BIE) > \underline{\beta}_W(BF)$ for all $\gamma > 0.58$. Hence, a global welfare loss under any of the BCA-regimes can only ocurr if $\gamma > 0.83$.

- For country 1, $W_1^{BI*} \leq W_1^{PB*}$ if $\beta \leq$(or $\geq$)$\frac{5}{13}(17\gamma - 2) - (+)\frac{3}{26}\sqrt{64\gamma(49\gamma - 10) - 113}$ for all $\gamma > 0.317$. The first inequality violates the NN-constraints and the second inequality violates the BCA-constraint. Therefore, we have $W_1^{BI*} > W_1^{PB*}$. Similar results are obtained by comparing the welfare level of country 1 under the PB-regime with the BIE- and BF-regime. That is, $W_1^{BIE*} > W_1^{PB*}$ if $\frac{(25\gamma-2)}{3} - \Psi < \beta < \frac{(25\gamma-2)}{3} + \Psi$ with $\Psi = \frac{\sqrt{3}\sqrt{848\gamma^2 - 128\gamma - 31}}{6}$, and $W_1^{BF*} > W_1^{PB*}$ if $\frac{2(11\gamma-1)}{3} - \Omega < \beta < \frac{2(11\gamma-1)}{3} + \Omega$ with $\Omega = \frac{\sqrt{800\gamma^2 - 128\gamma - 31}}{4}$, where these conditions hold given our NN- and BCA-constraints.

- For country 2, $W_2^{BI*} > W_2^{PB*}$ if and only if $\psi - \xi < \beta < \psi + \xi$, where $\psi = \frac{1}{11}(91 - 127\gamma)$ and $\xi = \frac{9}{44}\sqrt{2}\sqrt{32\gamma(49\gamma - 71) + 843}$. The NN-constraints guarantee the satisfaction of the first part of the above condition, $\psi - \xi < \beta$, which does not violate the BCA-constraint. With respect to the second part of the above condition, $\beta < \psi + \xi$, we have the following: *a)* the BCA-constraint assures the satisfaction of this condition for all $\gamma \in [0.5, 0.6275]$, *b)* for $\gamma \in (0.6275, 0.72503)$ country 2 might be better off if and only if the second part of the above condition holds, *c)* for all $\gamma \in [0.72503, 1]$, this condition violates the NN-constraint. Hence, $W_2^{BI*} > W_2^{PB*}$ for all $\gamma \in [0.5, 0.6275]$, while $W_2^{BI*} < W_2^{PB*}$ for all $\gamma \in [0.72503, 1]$. For the other two BCA-regimes, we have similar conditions, for instance $W_2^{BIE*} > W_2^{PB*}$ for all $\gamma \in [0.5, 0.59]$, while $W_2^{BIE*} < W_2^{PB*}$ for all $\gamma \in [0.7, 1]$, and $W_2^{BF*} > W_2^{PB*}$ for all $\gamma \in [0.5, 0.595]$, while $W_2^{BF*} < W_2^{PB*}$ for all $\gamma \in [0.655, 1]$.

3) Comparison across BCAs regimes:

- $W^{BIE*} \geq W^{BI*}$ if $\beta \leq 3\gamma - 2$ or if $\beta \geq \frac{1}{19}(89\gamma + 42)$. The first condition violates the NN-constraints, while the second condition violates the BCA-constraint. Therefore, $W^{BIE*} < W^{BI*}$. In addition, we find that $W^{BF*} < W^{BI*}$ for all values of γ.

- $W^{BF*} > W^{BIE*}$ if $\frac{1}{3}(13\gamma - 2) = \ddot{\beta} < \beta < \frac{1}{21}(19\gamma + 58)$ for all $\gamma < 1$. The first part of the inequality implies that the optimal rebate is larger than a full rebate, i.e., $\varphi^* > 1$, and the second inequality is satisfied by the BCA-constraint for all $\gamma < 0.7$. Therefore, $W^{BF*} \leq W^{BIE*}$ if $\beta \leq \ddot{\beta}$, i.e. if $\varphi^* \leq 1$, and if $\beta \geq \frac{1}{21}(19\gamma + 58)$ for all $\gamma \geq 0.7$.

B Appendix of Section 5

B.1 Proof of Lemma 1

i. From Appendices A.1 and A.3: $W_2^{FC*} \geq W_2^{BI*}$ if $\beta \geq \underline{\beta_1}(\gamma) = \frac{1}{11}(28 - \gamma)$ and/or if $\beta \leq 14 - 23\gamma \; \forall \; \gamma \geq 0.5$. The NN-constraints are not sufficient to guarantee the satisfaction of the first condition; thus it needs to hold. However, this condition violates the BCA-constraint for all $\gamma < 0.6025$. Recall that we consider only the range in which cooperation cannot be achieved under the PB-regime, i.e., $\gamma > \overline{\gamma} = 0.6406$ from Proposition 5. Therefore, the first condition does not violate the BCA-constraint in our range. The second condition violates the NN-constraint for all $\gamma \geq 0.57$. Hence, this condition is not relevant for the parameter range which we consider $\gamma > \overline{\gamma}$. As a result, if country 1 imposes the BI-threat, we have $W_2^{FC*} \geq W_2^{BI*}$ if $\beta \geq \underline{\beta_1}(\gamma)$, where $\frac{\partial \beta_1}{\partial \gamma} < 0$ for all γ.

ii. From Appendices A.1 and A.4: $W_2^{FC*} \geq W_2^{BIE*}$ if (a) $\gamma < 0.59$ and (b) if $\beta \geq$ (or $\leq$)$\frac{226-323\gamma}{39} + (-)\frac{4\sqrt{2}\sqrt{353\gamma^2-263\gamma+32}}{13}$ for all $\gamma \geq 0.59$. We consider the range: $\gamma > \overline{\gamma} = 0.6406$. The NN-constraints are not sufficient to guarantee the first condition in (b) and it also does not violate the BCA-constraint. As a result, this condition needs to hold. The second condition in (b) violates the NN-constraints. Therefore, for the range $\gamma > \overline{\gamma}$, if country 1 imposes the BIE-threat, $W_2^{FC*} \geq W_2^{BIE*}$ if $\beta \geq \underline{\beta_2}(\gamma) = \frac{226-323\gamma}{39} + \frac{4\sqrt{2}\sqrt{353\gamma^2-263\gamma+32}}{13}$, where $\frac{\partial \beta_2}{\partial \gamma} > 0$ for all $\gamma > 0.59$.

iii. $W_2^{FC*} \geq W_2^{BF*}$ if (a) $\gamma < 0.627$ and (b) if $\beta \geq$ (or $\leq$)$\frac{1}{3}(16 - 20\gamma) + (-)\sqrt{\gamma(46\gamma - 40) + 7}$ for all $\gamma \geq 0.627$. We consider the range: $\gamma > \overline{\gamma} = 0.6406$.

The NN-constraints are not sufficient to guarantee the first condition in (b) and it also does not violate the BCA-constraint. Thus, this condition needs to hold. The second condition in (b) violates the NN-constraints for all $\gamma \geq 0.628$ and hence is not relevant here. Therefore, for the range $\gamma > \overline{\gamma}$, if country 1 imposes the BF-threat, $W_2^{FC*} \geq W_2^{BF*}$ if $\beta \geq \underline{\beta_3}(\gamma) = \frac{1}{3}(16 - 20\gamma) + \sqrt{\gamma(46\gamma - 40) + 7}$, where $\frac{\partial \beta_3}{\partial \gamma} > 0$ for all $\gamma > 0.627$.

In addition, we have $\underline{\beta_1}(\gamma) > \underline{\beta_2}(\gamma) > \underline{\beta_2}(\gamma)$ for all $\gamma > \overline{\gamma}$.

B.2 Proof of Lemma 2

i. As mentioned in Proposition 5, $W_1^{FC*} \geq W_1^{PB*}$ for all $\gamma \geq \frac{23}{64} \simeq 0.36$, which holds as we assume $\gamma \geq 0.5$.

ii. From Appendices A.1 and A.3: $W_1^{FC*} \geq W_1^{BI*}$ if (a) $\beta \leq \overline{\beta_1}(\gamma) = \frac{1}{13}(\gamma + 32)$ and/or (b) if $\beta \geq 13\gamma - 4$ for all $\gamma \geq 0.5$. The inequality in (a) does not violate the NN-constraint, but the BCA-constraint is not sufficient to guarantee this condition for all $\gamma \geq 0.6$. Hence, for all $\gamma > \overline{\gamma}$, the inequality in (a) needs to hold. The inequality in (b) violates the BCA-constraint. Therefore, $W_1^{FC*} \geq W_1^{BI*}$ if $\beta \leq \overline{\beta_1}(\gamma)$, where $\frac{\partial \overline{\beta_1}}{\partial \gamma} > 0$.

iii. From Appendices A.1 and A.4: $W_1^{FC*} \geq W_1^{BIE*}$ if $\beta \leq$ (or $\geq$)$\frac{1}{3}(25\gamma - 2) - (+)\frac{2}{3}\sqrt{3}\sqrt{53\gamma^2 - 44\gamma + 11}$. The first condition does not violate the NN-constraint and can be satisfied as long as the BCA-constraint holds if $\gamma \leq 0.548$. However, for all $\gamma > \overline{\gamma}$, the BCA-constraint is not sufficient and this condition needs to hold. The second condition violates the BCA-constraint for all γ. Therefore, for all $\gamma > \overline{\gamma}$, we have $W_1^{FC*} \geq W_1^{BIE*}$ if $\beta \leq \overline{\beta_2}(\gamma) = \frac{1}{3}(25\gamma - 2) - \frac{2}{3}\sqrt{3}\sqrt{53\gamma^2 - 44\gamma + 11}$, where $\frac{\partial \overline{\beta_2}}{\partial \gamma} > 0$.

v. As shown in the proof of Proposition 5 in Appendix A.10, country 1 is always better off under all BCA-regimes than under the PB-regime.

B.3 Proof of Proposition 6

Using Lemma 1 and 2, we solve the game by backward induction. We start with the cooperative region, i.e., cooperation can be established with one of the BCA-threats and then consider the non-cooperative region, i.e., cooperation cannot be established. Recall that the escalating penalty game starts from $\gamma > \overline{\gamma}$ (see Assumption 1).

1) Cooperative Region

In stage III, country 2 faces the BF-threat and can either cooperate or not. Country 2 cooperates if $\beta \geq \underline{\beta_3}(\gamma)$ and ends at node 8 in Figure 2. Country 1 will only use the BF-threat to establish cooperation if it is better off under cooperation than if it implemented the BIE-regime earlier (ending at node 7). That is, we must have: $W_1^{FC*} \geq W_1^{BIE*}$, which is true if $\beta \leq \overline{\beta_2}(\gamma)$. Finally, country 1 would only implement the BIE-regime if the BIE-threat did not lead to cooperation. That is, $\beta < \underline{\beta_2}(\gamma)$. In other words, the game has progressed to stage III. Thus, in stage III, in order for cooperation to be an equilibrium path, we need $\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$ and $\beta \leq \overline{\beta_2}(\gamma)$. Since we have $\underline{\beta_2}(\gamma) < \overline{\beta_2}(\gamma)$, cooperation is an equilibrium path if $\underline{\beta_2}(\gamma) > \beta \geq \underline{\beta_3}(\gamma)$.

In stage II, country 2 faces the BIE-threat and can either cooperate or not. Country 2 chooses no cooperation if $\beta < \underline{\beta_2}(\gamma)$ and we end up in Stage III as described above. Instead, country 2 chooses cooperation in stage II if $\beta \geq \underline{\beta_2}(\gamma)$, and we end up in node 6. Country 1 will only use the BIE-threat to establish cooperation if it is better off under cooperation than if it implemented the BI-regime earlier on (node 5). That is, we must have: $W_1^{FC*} \geq W_1^{BI*}$, which is true if $\beta \leq \overline{\beta_1}(\gamma)$. Finally, country 1 would only implement the BI-regime if the BI-threat did not lead to cooperation. That is, $\beta < \underline{\beta_1}(\gamma)$. This means the game has progressed to stage II. Thus, in stage II, in order for cooperation to be an equilibrium path, we need $\underline{\beta_1}(\gamma) > \beta \geq \underline{\beta_2}(\gamma)$ and $\beta \leq \overline{\beta_1}(\gamma)$. Since we have $\underline{\beta_1} < \overline{\beta_1}(\gamma)$, cooperation is an equilibrium path if $\underline{\beta_1}(\gamma) > \beta \geq \underline{\beta_2}(\gamma)$.

In stage I, country 2 faces the BI-threat and can either cooperate or not. Country 2 chooses no cooperation if $\beta < \underline{\beta_1}(\gamma)$, and we end up in stage II as described above. Instead, country 2 chooses cooperation in stage I if $\beta \geq \underline{\beta_1}(\gamma)$, and we end up in node 4 in Figure 2. Country 1 will only use the BI-threat to establish cooperation if it is better off under cooperation than if it implemented the PB-regime earlier on (node 3). That is, we must have: $W_1^{FC*} \geq W_1^{PB*}$, which we know always holds (see Lemma 2). Finally, country 1 would only implement the BI-threat if country 2 did not accept its proposal for cooperation in stage 0, which was our starting point as we assume $\gamma > \overline{\gamma}$. Thus, in stage I, in order for cooperation to be an equilibrium path, we need $\beta \geq \underline{\beta_1}(\gamma)$ and $\gamma > \overline{\gamma}$.

2) Non-cooperative Region

First, we have shown in Proposition 5 and Lemma 2 that country 1 is better off under any of the BCA-regimes than under the PB-regime. Hence, node 3 is never an equilibrium outcome in the non-cooperative region.

Second, solving $W_1^{BIE*} \geq W_1^{BI*}$ gives two conditions: (a) $\beta \leq 3\gamma - 2$ and (b) $\beta \geq 2\gamma$. The first condition violates the NN-constraint. The second condition does not violate the BCA-constraint, and the NN-constraint is not sufficient to guarantee this condition; thus, it needs to hold. Therefore, $W_1^{BIE*} > (\leq) W_1^{BI*}$ if $\beta > (\leq) 2\gamma$.

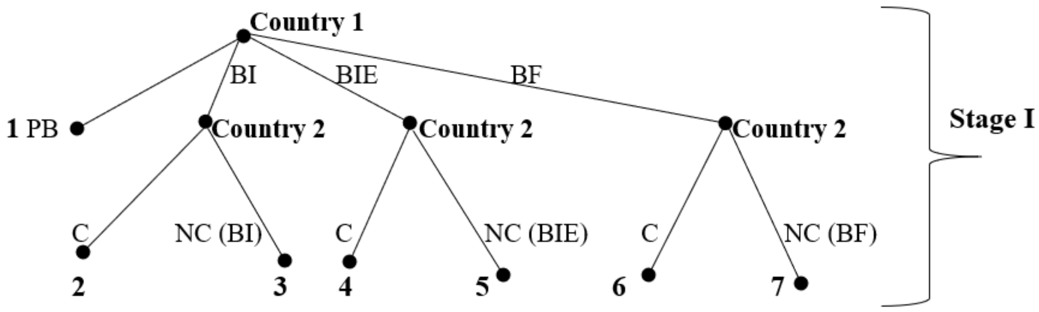
Third, the BF-regime is dominated by the BIE-regime for country 1 and hence if $\underline{\beta_3}(\gamma) > \beta > 2\gamma$, country 1 chooses the BIE-regime, while if $\beta \leq 2\gamma$, country 1 chooses the BI-regime.

Note that if $\beta = 2\gamma$, country 1 is indifferent between the BI- and the BIE-regime. Therefore, we assume that country 1 chooses the BI-regime according to the Pareto-criterion. That is, we find $W_2^{BIE*} > W_2^{BI*}$ if and only if $\frac{7}{29}(\gamma - 6) < \beta < (3\gamma - 2)$. The first inequality is satisfied as long as $\beta > 0$; however, the second inequality violates the NN-constraint. Therefore, $W_2^{BIE*} < W_2^{BI*}$.

B.4 One-stage Penalty Game

Suppose stages I, II, and III do not take place sequentially according to the escalating penalty path depicted in Figure 2, but are reduced to stage I as in the Figure below.

That is, country 1 can choose either of the three BCA-regimes to enforce cooperation right from the beginning. That is, the game tree would look as follows:



As mentioned in the text, country 1 starts to use BCA-threats if country 2 refuses the proposal 'cooperation' in stage 0, which is our starting point as in Figure 2. That is, $W_1^{FC*} > W_1^{PB*}$, $W_1^{BI*} > W_1^{PB*}$, $W_1^{BIE*} > W_1^{PB*}$ and $W_1^{BF*} > W_1^{PB*}$, as shown in Appendices A.10 and B.2, and $W_2^{FC*} < W_2^{PB*}$ if $\gamma > \overline{\gamma}$ according to Proposition 5.

If $\beta \geq \underline{\beta_1}(\gamma)$, cooperation (C) is established by the three BCA-measures and we have three subgame-perfect Nash equilibria: BI→C, BIE→C and BF→C, corresponding to endnodes 2, 4 and 6. If $\underline{\beta_1}(\gamma) > \beta \geq \underline{\beta_2}(\gamma)$, we have two subgame-perfect equilibria: BIE→C and BF→C, corresponding to endnodes 4 and 6 and finally for $\underline{\beta_2} > \beta \geq \underline{\beta_3}(\gamma)$, the subgame-perfect equilibrium is BF→C with endnode 6. For $\beta < \underline{\beta_3}$, the outcome is no cooperation (NC), with endnode 5 if $\underline{\beta_3} > \beta > 2\gamma$ because $W_1^{BIE*} > W_1^{BI*}$, whereas if $2\gamma \geq \beta$, endnode 3 would emerge because $W_1^{BIE*} \leq W_1^{BI*}$. Thus, only for $\beta < \underline{\beta_2}$ would we have a unique equilibrium, but not for $\beta \geq \underline{\beta_2}$. However, all other qualitative results would be the same as in Proposition 6.

B.5 Proof of Corollary 2

i. As shown in Appendix A.10, the global welfare gap is given by $\Delta W = \frac{9}{16}d^2$, which increases in d at an increasing rate. We showed in Proposition 6 that full cooperation cannot be achieved if $\underline{\beta_3}(\gamma) > \beta$, i.e., if $\frac{A}{d}$ is low or equivalently if d is high, given A.

ii. Inserting the global welfare levels using Appendix A into (10) in the text, we obtain:

First, $CGI_W^{BI} = \frac{d^2((160\gamma-170\gamma^2-71)+4Ad(\gamma+152)-122A^2}{729d^2}$,

where $\frac{\partial CGI_W^{BI}}{\partial d} < 0$ if $\gamma > \frac{61A-152d}{d}$ and $\frac{61A-152d}{d} \leq 0$ if $\beta \leq \frac{152}{61} \simeq 2.492$. The BI-regime is implemented if $\beta \leq 2\gamma$, where $2\gamma < \frac{152}{61}$ for all γ. Thus, we always have $\frac{\partial CGI_W^{BI}}{\partial d} < 0$ in the non-cooperative region.

Second, $CGI_W^{BIE} = \frac{d^2\left(268\gamma-73\gamma^2-226\right)-138Ad\left(\gamma-\frac{202}{23}\right)-225A^2}{1458d^2}$,

where $\frac{\partial CGI_W^{BIE}}{\partial d} < 0$ if $\gamma < \frac{202d-75A}{23d}$ and $\frac{202d-75A}{23d} > 1$ if $\beta < \frac{179}{75} \simeq 2.386$. The BIE-regime is implemented if $\beta < \underline{\beta_3}(\gamma)$, and we have $\underline{\beta_3}(\gamma) < \frac{179}{75}$ for all $\gamma \in [0.62, 1.29]$. Recall that the escalating penalty game starts from $\gamma > 0.64$ (see Assumption 1) and $\gamma \leq 1$. Hence, $\frac{\partial CGI_W^{BI}}{\partial d} < 0$ in the non-cooperative region.

Third, $CGI_W^{BF} = \frac{d^2\left(-160\gamma^2-224\gamma-55\right)+96Ad(\gamma+7)-144A^2}{729d^2}$, where $\frac{\partial CGI_W^{BF}}{\partial d} < 0$ if $\gamma > \frac{3A-7d}{d}$ and $\frac{3A-7d}{d} \leq 0$ if $\beta \leq \frac{7}{3} \backsimeq 2.33$. The BF regime could be implemented if $\beta < \underline{\beta_3}(\gamma)$, and we have $\underline{\beta_3}(\gamma) < \frac{7}{3}$ for all $\gamma \in [0.62, 1.29]$. Hence, $\frac{\partial CGI_W^{BF}}{\partial d} < 0$ in the non-cooperative region.

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