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Trade tariffs and self-enforcing environmental agreements*

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Abstract

In the basic model of international environmental agreements (IEAs) (Barrett 1994, Rubio and Ulph 2006) extended by international trade, self-enforcing - or stable - IEAs may comprise up to 60 % of all countries (Eichner and Pethig 2013). But these IEAs reduce total emissions only slightly compared to non-cooperation. Here we analyze the capacity of sign-unconstrained tariffs to enhance the size and performance of self-enforcing IEAs. We show that the size of stable IEAs shrinks when climate coalitions are Stackelberg leaders and set tariffs in addition to their cap-and-trade schemes. Surprisingly, these smaller IEAs reduce total emissions more effectively than the larger stable IEAs without tariffs. In the model with tariffs the signatory countries import fossil fuel and their tariff takes the form of a subsidy of fuel consumption and a tax on the production of the consumption good.

JEL classification:	C72, F18, Q50, Q58
Key words:	tariff, trade, self-enforcing environmental agreements, Stackelberg equilibrium

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1 The problem

International environmental agreements (IEAs) are essential for the stabilization of the world climate at safe levels because non-cooperative actions fail to achieve an effective reduction of global carbon emissions. The first legally binding international agreement on climate protection, the Kyoto Protocol, stipulated commitments for a small number of countries only and therefore accomplished very little in terms of global emission reduction. The prospects are bleak for reaching an IEA in the near future that attracts many signatories and reduces global emissions effectively. The tedious practical negotiations and the serious global climate change challenge call for continued investigations of the theoretical foundations of successful and effective IEAs.

Since the early 1990s an economic literature has developed on IEAs focusing on self-enforcement. An IEA is said to be self-enforcing or stable if no signatory country has an incentive to leave the IEA and no non-signatory country has an incentive to join. The seminal papers on self-enforcing IEAs include Barrett (1994), Hoel (1992) and Carraro and Siniscalco (1993). Most papers are pessimistic about the stability of *large* IEAs. Carraro and Siniscalco (1991), Hoel (1992) and Finus (2001) find that a stable IEA consists of three countries when the climate damage is linear and of two countries only when the climate damage is quadratic. These papers assume that both signatories and non-signatories behave in a Cournot-Nash fashion. Another strand of the IEA literature which we will follow in the present paper portrays the climate coalition as Stackelberg leader and all non-cooperative countries as Stackelberg followers. Diamantoudi and Sartzetakis (2006) and Rubio and Ulph (2006) proved that with the Stackelberg assumption the number of signatories of self-enforcing IEAs is not larger than four.

The basic model of an IEA employed by Barrett (1994), Diamantoudi and Sartzetakis (2006), Rubio and Ulph (2006) and others is a simple static model of symmetric countries. Each country's domestic carbon emissions generate domestic welfare that is decreasing at the margin and all countries' emissions create a welfare loss (climate damage) which is uniform across countries and increasing at the margin.[1] That model has been extended in various directions (Finus 2003). For example, Hoel and Schneider (1997) introduce transfer schemes in the coalition formation process, Kolstad (2007) studies systematic uncertainty and Carbone et al. (2009) use the basic model for an empirical investigation of how international emission trading impacts on IEAs.[2] Eichner and Pethig (2013) extend the basic

[1]Barrett (1994) models abatement, and therefore his approach seems to differ from the basic model, at first glance. However, as pointed out by Diamantoudi and Sartzetakis (2006, Section 4), Barrett's model is equivalent to the basic model as long as abatement does not exceed the flow of emissions.

[2]There are also studies relaxing the assumption of the basic model that countries are identical (e.g.

model by accounting for production, consumption, competitive markets and international trade.[3] Governments operate domestic cap-and-trade schemes keeping an eye on improving the terms of trade. Eichner and Pethig conclude that, depending on parameter constellations, international trade may significantly increase the size of stable IEAs compared to the autarky scenario,[4] but in all those IEAs world emissions are only slightly lower than in business as usual (BAU). The result that neither large nor small stable IEAs are effective in fighting climate change supports the disturbing view that efforts to strive for self-enforcing IEAs (of whatever size) are futile.[5] The natural question arises what can be done to overcome that disappointing outcome.

Rauscher (2005) suggests that trade policy may be "... a means to stabilize IEAs. Trade restrictions can be used as sanctions to enforce compliance." To investigate the impact of trade policy[6] on stable IEAs, the present paper extends Eichner and Pethig's (2013) model of the world economy with international trade by endowing the governments with a tariff in addition to their cap-and-trade scheme. The sign-unconstrained tariff enables countries to push the domestic fossil energy price for consumers and producers above or below the world market price. We aim at investigating the impact of the combined tariff and cap-and-trade regulation on the stability of coalitions and on their size and effectiveness. Our motivation for the analysis of that kind of overlapping regulation is that both types of instruments provide the governments with a lever for improving their terms of trade, (here: the world market price of fossil energy). As coalitions are typically larger than individual fringe countries, their 'market power' is superior and so is their capacity of improving their terms of trade. The question is whether through combining both instruments the coalition

Barrett 2001). In the present paper we will stick to that assumption to keep our model tractable.

[3]Despite the importance of international trade for the formation of IEAs, to our knowledge there is only one other theoretical paper dealing with that issue, and that is Barrett (1997) who illustrates in a partial equilibrium model with imperfect competition and abatement how trade policy may help support stable IEAs. The relevance of the link between international trade and mitigation policies is emphasized and discussed in a 'Symposium on Climate Change Policies and the World Trading System' (The World Economy 2011, Vol. 34, Issue 11).

[4]The autarky scenario in Eichner and Pethig (2013) is equal to the basic model of the literature in which the size of stable coalitions is always very small as mentioned above.

[5]Eichner and Pethig (2013) also show that it is not only in the free-trade scenario that world emissions are hardly reduced compared to BAU but also in the state of autarky which in their model coincides with the basic model of the literature alluded to above.

[6]Trade restrictions may not be compatible with WTO rules. GATT Article XX on general exceptions lays out a number of specific instances in which WTO members may be exempted from GATT rules. These exemptions include policy measures that are necessary to protect human, animal or plant life (Article XX paragraph b) or policy measures that are related to the conservation of exhaustible natural resources (Article XX paragraph g). Further information on a trade and environment debate in the WTO can be found in Charnovitz (2007).

is able to further strengthen its superior market power such that the size and performance of the stable coalition improve.

There is a large literature on the interaction of international trade, the environment and environmental policy, but the literature dealing with global environmental externalities is relatively small. An important contribution to the issue at hand is Copeland and Taylor (2005) who have thoroughly analyzed the effects and repercussions on trade and welfare of (unilateral) emission reduction policies. Their static general equilibrium model is more general than ours, in particular, because it allows for heterogeneous countries and the interaction between trade-induced income effects and environmental policy. However, it does not deal with tax policies overlapping with environmental regulation. An overlap similar to the one we will analyze is considered by Markusen (1975) and Copeland (1994). Copeland's (1994) focus is only on exogenous policy shocks in a small open economy. Markusen (1975) analyzes the unilateral tackling of the global environmental externality in a general equilibrium model and points out that the second-best tariff is used to improve the terms of trade and to internalize the environmental externality. If the country is an importer, it sets a positive import tariff. More recently, Ferrara et al. (2009) analyze the effects of uniform and discriminatory tariffs on countries' choices over environmental standards. Chen and Woodland (2013) provide a comprehensive (although still selective) review of the literature on international trade policies, environmental regulation and climate change. However, to the best of our knowledge none of the papers of that literature address the formation of stable coalitions. The present paper aims to fill that gap.

The tariff instrument we will focus on turns out to produce a number of unexpected effects. Most remarkable is, in our view, that the size of the stable coalition is always smaller with than without tariffs where the difference in size depends on parameter constellations. Nonetheless, the tariff improves the welfare of all countries and the effectiveness of total emission reduction. For the non-cooperating countries as well as for the members of the coalition it is advantageous to impose a negative tariff which amounts to subsidizing the consumption of fossil fuel and taxing the production of the consumption good. The tariff rates are much higher in absolute terms in the coalition than in the non-cooperating countries.

The paper is organized as follows. Section 2 introduces the model and briefly analyzes the business-as-usual scenario which serves as a benchmark throughout the paper. Section 3 characterizes the outcome of the Stackelberg game and its dependence on coalitions of given size. Section 4 is the core of the paper and analyzes self-enforcing IEAs. Section 5 employs the role of the tariffs and Section 6 concludes.

2 The model

The world economy consists of n identical countries. Each country produces two consumer goods. The first is a standard composite good, called *good* X (quantity x_i) and the second is a fossil energy carrier (quantity e_i), e.g. oil, gas or coal extracted from domestic fossil reserves. We refer to that good simply as *fuel*.[7] Each country's production technology is represented by the production possibility frontier[8]

$$x_i^s = T(e_i^s) \quad i = 1, \dots, n, \tag{1}$$

where the function T is decreasing and strictly concave in e_i^s. The transformation function (1) implies that both commodities are produced by means of domestic productive factors (e.g. labor and capital) whose endowments are given. The utility[9]

$$V(e_i^d) + x_i^d - D\left(\sum_j e_j^d\right) \tag{2}$$

of the representative consumer of country i is additive separable in all arguments and linear in the consumption x_i^d of good X. V is increasing and concave, and D is increasing and convex in its argument. The consumption of fuel generates the greenhouse gas carbon dioxide whose emission is proportional to fuel consumption. Emission units are chosen such that e_i^d denotes both fuel demanded by consumer i and carbon emissions from burning fuel. The function D captures the climate damage caused by worldwide carbon emissions from burning fuel.

For the sake of more specific results, we will specify the functions T, V and D from (1) and (2) by the following quadratic functional forms:[10]

$$T(e_i^s) = \bar{x} - \frac{\alpha}{2}\left(e_i^s\right)^2, \quad V(e_i^d) = ae_i^d - \frac{b}{2}(e_i^d)^2, \quad D\left(\sum_j e_j^d\right) = \frac{\delta}{2}\left(\sum_j e_j^d\right)^2, \tag{3}$$

where $\bar{x}$, a, b, α and δ are positive parameters.

[7] Households do not consume fuel directly but use fuel as input in a linear household production function to produce e.g. the commodity heat or transportation services. In our paper we omit the household production technology and simply interpret fuel as consumer good.

[8] The superscript s indicates quantities supplied. Upper-case letters denote functions. Subscripts attached to them indicate partial derivatives.

[9] The superscript d indicates quantities demanded.

[10] In (3) the parametric form of $T(e_i^s)$ can be 'microfounded' as follows. Let $\bar{r}$ be country i's endowment of a (composite) production factor and consider the production functions $x = \alpha_x r_x$ and $e = (r_e/\alpha_e)^{1/2}$ with $r_e + r_x = \bar{r}$. α_e, α_x are positive constants. The quadratic transformation function in (3) is straightforward from these three equations when setting $\bar{x} := \alpha_x \bar{r}$ and $\alpha := \alpha_x \alpha_e$.

There are perfectly competitive world markets for good X (price $p_x \equiv 1$) and for fuel (price p), and the markets are in equilibrium if

$$\sum_j x_j^s = \sum_j x_j^d \quad \text{and} \quad \sum_j e_j^s = \sum_j e_j^d. \tag{4}$$

To reduce carbon emissions, each government fixes a (binding) national emission cap, $e_i > 0$, and implements it by auctioning the amount e_i of emission permits at the permit price π_i. In addition, the governments are assumed to dispose of (sign-unconstrained) trade tariffs which either take the standard form of taxing imports (import tariffs) or of taxing exports. The tariff decouples the domestic fuel price from the world market fuel price, p, such that domestic producers *and* consumers face the price[11] $p+t_i$, $t_i \in \mathbb{R}$. If $t_i > 0$ [$t_i < 0$], the tariff is equivalent to a tax [subsidy] on fuel consumption, combined with a subsidy [tax] on fuel production which stimulates [curbs] fuel production. Thus, ceteris paribus, the government reduces [increases] the net trade flow $(e_i^d - e_i^s) \in \mathbb{R}$, if it chooses $t_i > 0$ [$t_i < 0$]. Since we allow for $t_i \in \mathbb{R}$, we refer to the trade policy instrument as 'tariff' rather than 'import tariff'.

Taking the tariff rate t_i as given, the (aggregate) producer in country i maximizes profits $x_i^s + (p+t_i)e_i^s$ subject to (1). The first-order condition is

$$p + t_i = -T'(e_i^s) \quad \text{or} \quad e_i^s = \frac{p+t_i}{\alpha}, \tag{5}$$

where the second equation in (5) holds for the quadratic transformation function (3). The representative consumer in country i ignores the impact of her emissions on climate damage and maximizes her consumption utility $V(e_i^d) + x_i^d$ subject to her budget constraint[12]

$$x_i^d + (p + \pi_i + t_i)e_i^d = y_i, \quad \text{where} \quad y_i := x_i^s + (p+t_i)e_i^s + \pi_i e_i^d + t_i(e_i^d - e_i^s) \tag{6}$$

is consumer i's income.[13] From the first-order condition $p + \pi_i + t_i = V'(e_i^d)$ follows the fuel demand function, say $e_i^d = E^d(p + \pi_i + t_i)$. The domestic permit market is in equilibrium, if

$$e_i = E^d(p + \pi_i + t_i). \tag{7}$$

[11]Consumers also pay the price π_i for emission permits. Since each fuel is assumed to generate one unit of carbon emissions, the permit price π is equivalent to a tax on fuel consumption such that $p + t_i + \pi_i$ is the *effective* consumer price of fuel.

[12]Rearranging (6) yields $x_i^d - x_i^s = p(e_i^s - e_i^d)$ which demonstrates that p represents the terms of trade and that the world market for good X is in equilibrium, if and only if the world market for fuel is in equilibrium (Walras Law).

[13]The income consists of profit income, $x_i^s + (p+t_i)e_i^s$, plus revenues from auctioning permits, $\pi_i e_i^d$, and tariff revenues, $t_i(e_i^d - e_i^s)$.

For given fuel market price p and fixed policy instruments (e_i, t_i) equation (7) determines the equilibrium permit price π_i. The determination of π_i is the only purpose of (7); neither (7) nor π_i will play a role in the subsequent analysis.

Combining the equilibrium condition of the world fuel market, $\sum_j e_j^s = \sum_j e_j^d$, from (4) with the policy constraints $e_i^d = e_i$ for $i = 1, \ldots, n$, yields

$$p = \frac{\alpha \sum_j e_j}{n} - \frac{\sum_j t_j}{n} \quad \text{for } i = 1, \ldots, n, \tag{8}$$

which in turn establishes

$$e_i^s = \frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha} \quad \text{for } i = 1, \ldots, n \tag{9}$$

after insertion in (5). Equation (8) determines the unique equilibrium world market price of fuel (= terms of trade). According to (8) each country i affects - and may manipulate in its own favor - the terms of trade through variations of its policy parameters (e_i, t_i). Inserting (8) in (1) as well as (8) and (9) in (7), we obtain the equilibrium supplies and demands on the market for good X as

$$\begin{aligned} x_i^s &= T\left(\frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha}\right) && (10) \\ x_i^d &= x_i^s + p(e_i^s - e_i) \\ &= T\left(\frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha}\right) + \left(\frac{\alpha \sum e_j}{n} - \frac{\sum_j t_j}{n}\right) \cdot \left[\frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha} - e_i\right]. && (11) \end{aligned}$$

Combining (2) with $e_i^d = e_i$ and (11) yields the welfare function of country i,

$$\begin{aligned} W^i(e_1, \ldots, e_n, t_1, \ldots, t_n) \;:=\; & V(e_i) + \bar{x} - \frac{\alpha}{2}\left(\frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha}\right)^2 \\ & + \left(\frac{\alpha \sum e_j}{n} - \frac{\sum_j t_j}{n}\right) \cdot \left[\frac{\sum_j e_j}{n} - \frac{\sum_j t_j}{\alpha n} + \frac{t_i}{\alpha} - e_i\right] - D\left(\sum_j e_j\right). \quad (12) \end{aligned}$$

For the later use as benchmark, we briefly characterize the non-cooperative Nash equilibrium which we refer to as business as usual (BAU). Each government sets its emission cap and tariff taking as given the emission caps and tariffs of the other countries. Differentiation of $W^i(e_1, \ldots, e_n, t_1, \ldots, t_n)$ with respect to e_i and t_i yields the first-order conditions

$$\begin{aligned} W_{e_i}^i &= V'(e_i) - \frac{\alpha}{n} e_i - \frac{(n-1)}{n}\left(\frac{\alpha \sum_j e_j}{n} - \frac{\sum_j t_j}{n}\right) - D'\left(\sum_j e_j\right) = 0, && (13) \\ W_{t_i}^i &= -\frac{t_i}{\alpha} + \frac{\sum_j t_j}{\alpha n^2} - \frac{1}{n}\left(\frac{\sum_j e_j}{n} - e_i\right) = 0, && (14) \end{aligned}$$

for $i = 1, \ldots, n$. Since countries are alike, we impose symmetry and prove in Appendix A

Result 1. *If all countries act non-cooperatively, the symmetric Nash equilibrium is characterized by* $e_i = e_j = \frac{a}{\alpha+b+\delta n} =: e_{BAU}$ *and* $t_i = t_j = 0$ *for* $i, j = 1, \ldots, n$*, and there is no international trade.*

Since countries are identical in the symmetric Nash equilibrium, they choose the same emission cap and the same tariff. Using that information in (9) countries have the same fuel supply. As a consequence there is no fuel trade and there are no incentives for countries to manipulate the fuel price. That is the reason for the observation in Result 1 that all countries refrain from setting tariffs in BAU. It is also clear that total emissions ne_{BAU} exceed total emissions in the optimal fully cooperative solution, since all countries disregard in BAU the positive external effects of their emission reduction on the other countries.

3 Coalitions of given size as Stackelberg leader

Suppose now that some countries are members in a climate coalition, whereas all other countries continue to act non-cooperatively. For the sake of formal analysis, we lump together the first m countries in one group, denoted group $C := 1, 2, \ldots, m$ with C for coalition, and collect all remaining countries in another group, denoted group $F := m+1, \ldots, n$ with F for fringe. Our focus will be on a game of sequential choice of strategies that consist of an emission cap and a tariff. The coalition is the Stackelberg leader and moves first, and the fringe countries are Stackelberg followers. The coalition formation literature has made ample use of the Stackelberg assumption (Finus 2003), and we refer the reader to that literature for the discussion about the plausibility and relative merits of the Nash concept on the one hand and the Stackelberg concept on the other. Our aim is to investigate how the Stackelberg assumption drives the outcome of the game when we extend the basic model as outlined in Section 2. In the present section we aim to investigate the Stackelberg approach for *given* coalition sizes and thus prepare for the analysis of coalition stability in the next Section 4.

Concept of Stackelberg equilibrium. We focus on scenarios, in which all countries within one group are treated equally. It is therefore both possible and convenient to proceed by setting $e_i = e_c$, $t_i = t_c$ for all $i \in C$ and $e_i = e_f$, $t_i = t_f$ for all $i \in F$. In addition, we denote the groups' total emissions by $s_c := me_c$ and $s_f := (n-m)e_f$, respectively. We keep portraying the fringe countries as non-cooperative Nash players. Hence for $i \in F$ the first-order conditions (13) and (14) still determine an individual fringe country's best reply to given caps and tariffs of all other countries. For analytical convenience, we invoke the parametric functions (3) and insert in (13) and (14): $e_i = \frac{s_f}{n-m}$, $t_i = t_f$, $\sum_j e_j = s_c + s_f$ and $\sum_j t_j = mt_c + (n-m)t_f$. Then we solve (13) and (14) for s_f and t_f and obtain, as shown in Appendix B, two reaction functions

$$s_f = R^\sigma(s_c, t_c; m) \quad \text{and} \quad t_f = R^\tau(s_c, t_c; m). \tag{15}$$

R^σ and R^τ are additively separable and have constant partial derivatives $R^v_{s_c} < 0, R^v_{t_c} > 0$ for $v = \sigma, \tau$. According to (15) the fringe countries can be treated as if they act as a single player whose strategy is (s_f, t_f). In that sense R^σ and R^τ are the 'aggregate' best reply functions of 'the fringe'. However, it is important to emphasize that the equations (15) are equivalent to (13) and (14) for $i \in F$. Therefore (15) does not imply any cooperation among fringe countries.

With the new notation (s_c, t_c, s_f, t_f) we rewrite the welfare (12) of the individual countries as

$$\begin{aligned} W^c(s_c, t_c, s_f, t_f; m) \quad &:= \quad V\left(\frac{s_c}{m}\right) + \bar{x} - \frac{t_c^2}{2\alpha} + \frac{[\alpha(s_c + s_f) - mt_c + (n-m)t_f]^2}{2\alpha n^2} \\ &- \quad \frac{s_c[\alpha(s_c + s_f) - mt_c + (n-m)t_f]}{nm} - D(s_c + s_f), \end{aligned} \tag{16}$$

$$\begin{aligned} W^f(s_c, t_c, s_f, t_f; m) \quad &:= \quad V\left(\frac{s_f}{n-m}\right) + \bar{x} - \frac{t_f^2}{2\alpha} + \frac{[\alpha(s_c + s_f) - mt_c + (n-m)t_f]^2}{2\alpha n^2} \\ &- \quad \frac{s_f[\alpha(s_c + s_f) - mt_c + (n-m)t_f]}{n(n-m)} - D(s_c + s_f). \end{aligned} \tag{17}$$

The coalition's objective function is the aggregate welfare of its members, $mW^c(s_c, t_c, s_f, t_f; m)$. Acting as Stackelberg leader, the coalition maximizes $mW^c(\cdot)$ with respect to (s_c, t_c) subject to (15). The Stackelberg equilibrium is given by the strategy quadruple $(s_c^*, t_c^*, s_f^*, t_f^*)$, where

$$(s_c^*, t_c^*) := \arg\max_{(s_c, t_c)} mW^c\left[s_c, t_c, R^\sigma(s_c, t_c; m), R^\tau(s_c, t_c; m); m\right],$$

and where $s_f^* = R^\sigma(s_c^*, t_c^*; m)$ and $t_f^* = R^\tau(s_c^*, t_c^*; m)$ are the fringe countries' aggregate responses to (s_c^*, t_c^*). It follows that the equilibrium welfare of all countries is fully determined by the coalition size m:

$$\mathcal{W}^{kt}(m) := W^k[s_c^*, t_c^*, R^\sigma(s_c^*, t_c^*; m), R^\tau(s_c^*, t_c^*; m); m] \quad \text{for} \quad k = c, f. \tag{18}$$

Since the equilibrium strategies necessarily satisfy the best-reply functions of the fringe, (15), these functions deserve our special attention. Suppose first that $t_c = t_f = 0$.[14] In that case we find that $R^\sigma_{s_c} \in]-1, 0[$ and therefore (i) the emissions of the coalition and the fringe are strategic substitutes and (ii) an emission reduction $\Delta s_c < 0$ [emission increase $\Delta s_c > 0$] on the part of the coalition shrinks [expands] total emissions, but by less than $\Delta s_c < 0$. In

[14]For details on the following discussion of the implications of $t_c = t_f = 0$ see Eichner and Pethig (2013).

the climate change literature this phenomenon is referred to as carbon leakage (for the case $\Delta s_c < 0$). The leakage rate is usually expressed by $\left|R^{\sigma}_{s_c}\right| \in]0,1[$. Note also that the increase in total emissions resulting from a given increase in the coalition countries' emissions is the larger, the larger the coalition size. That is, large coalitions are more effective in curbing total emissions, because the leakage rate is declining in the coalition size ($R^{\sigma}_{s_c m} > 0$). That observation conforms to intuition and will turn out to drive the results. Suppose now the governments make use of tariffs ($t_c, t_f \in \mathbb{R}$) in addition to fixing emission caps. If s_c is kept constant, the coalition curbs [increases] carbon leakage, if and only if $\Delta t_c < 0[\Delta t_c > 0]$. Thus the coalition's tariff rate affects the extent of carbon leakage. A second-order effect is, however, that fringe countries respond by shifting t_f in the same direction as t_c thus affecting fuel production and consumption in their countries and with it the equilibrium fuel price.

An obvious necessary condition for countries to be members of a coalition is that their welfare in the coalition is at least as high as their welfare in business as usual, $w_{\text{BAU}} \leq \mathcal{W}^{ct}(m)$. That condition is satisfied, indeed, because the coalition can always choose the strategy ($e_c = e_{\text{BAU}}, t_c = 0$) to which the fringe countries' best reply is ($e_f = e_{\text{BAU}}, t_f = 0$). Moreover, it can be shown that the strict inequality sign $\mathcal{W}^{ct}(m) > w_{\text{BAU}}$ holds for every coalition size $m \in \{1, \ldots, n\}$.[15]

Stackelberg equilibria and coalition size. It is clear from our analysis above that for given parameters a, b, $\bar{x}$, α, δ and n the Stackelberg equilibrium is uniquely determined by the coalition size m. In the following we investigate how the equilibrium allocation depends on and varies with the coalition size. To that end we focus on the functions $\mathcal{W}^{kt}$ for $k = c, f$ whose images, defined by (18), represent the welfare of coalition and fringe countries, respectively, in the Stackelberg equilibrium with coalition size m. We take the interval $[0, n] \subset \mathbb{R}_+$ to be the domain of these functions for analytical convenience, keeping in mind in our later conclusions that the domain of real-world coalitions is the set of integers $\{1, \ldots, n\}$. The coalition size not only determines welfares $\mathcal{W}^{kt}(m)$ in equilibrium, but also all other variables. To express their dependence on m we introduce further equilibrium functions analogous to $\mathcal{W}^{kt}$ and write $e_k = \mathcal{E}^{kt}(m)$, $\pi_k = \Pi^{kt}(m)$, $t_k = \mathcal{T}^{k}(m)$ and $p = \mathcal{P}^{kt}(m)$ for $k = c, f$. We also wish to compare these equilibrium functions with their counterparts in the model with stand-alone cap-and-trade schemes that have already been analyzed by Eichner and Pethig (2013). Their results will serve here as a benchmark for identifying the performance of tariffs as an overlapping policy instrument. To avoid confusion about equilibrium functions and variables in different models, we mark all of them with the index t as before in the model with two policy instruments and with the index o in the model of

[15]The Stackelberg leader's first-oder condition with respect to the tariff $\frac{\mathrm{d}mW^c}{\mathrm{d}t_c}$ evaluated at ($s_c = me_{\text{BAU}}, t_c = 0$) is strictly positive which proves that claim.

Eichner and Pethig (2013).[16]

Unfortunately, all these equilibrium functions depend on m in such a complex way that the analytical specification of their curvature is impossible. To make progress we resort to numerical examples. The Figures 1 through 8 below are calculated for the parameter values $a = 100$, $b = 20$, $\bar{x} = 12$, $\alpha = 1000$, $\delta = 10$ and $n = 10$. In these figures, all curves represent Stackelberg equilibrium values in case of coalitions with $m \in [1, 10]$ members.[17] Solid curves relate to the model in which the countries' strategies are (e_i, t_i), while all dashed curves relate to the model constrained by $t_c = t_f = 0$.

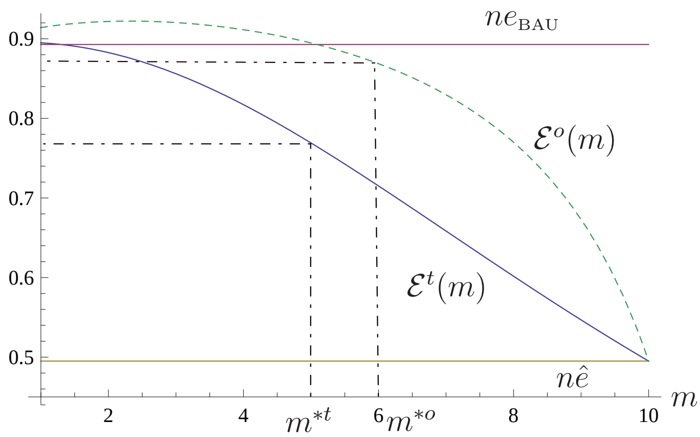

Figure 1: World emissions $[\mathcal{E}^z(m) := m\mathcal{E}^{cz}(m) + (n-m)\mathcal{E}^{fz}(m);\ z = o, t]$

In Figure 1 the difference between the horizontal straight lines, $ne_{\text{BAU}} - n\hat{e}$, measures the excess of total BAU emissions over total emissions in the social optimum. The lines ne_{BAU} and $n\hat{e}$ are the same with and without tariffs, because the tax rates are $t_c = t_f = 0$ in the scenarios of BAU and the social optimum irrespective of whether tariffs are at the governments' disposal. According to Figure 1 in case of tariffs coalitions of all sizes reduce total emissions compared to BAU,[18] total emissions are declining in m, and they are smaller with than without tariffs. Thus imposing tariffs - in addition to emission trading - turns out to be an effective means of fighting climate change.

To understand the forces driving that result, we take a closer look at the markets for fuel and permits and at the countries' cap-and-trade policies. Consider first Figure 2a that shows how countries choose emission caps when coalition sizes vary. The caps of coalition countries are strictly decreasing in m and their curvature is very similar with and without

[16]For example, w now write $\mathcal{W}^{kz}$, $k = c, f$ and $z = o, t$, where $\mathcal{W}^{ko}$ refers to the model with stand-alone cap-and-trade scheme and $\mathcal{W}^{kt}$ refers to the model with tariffs and cap-and-trade schemes.

[17]The Appendix D shows for the parametric example of the present section (with $m = 4$) that the Stackelberg leader's welfare function $mW^c(\cdot)$ is concave in its strategies s_c and t_c.

[18]Without tariffs, total emissions even exceed BAU emissions for small m. For more details see Eichner and Pethig (2013).

tariffs. For small m these caps exceed e_{BAU} and eventually drop below that level. However, tariffs make an enormous difference for the caps of fringe countries. With tariffs, their caps are below e_{BAU} for all m and rise only slightly in m. Without tariffs, their caps are below e_{BAU} for small m as well, but they sharply increase with m and exceed e_{BAU} for large m. Thus through its choice of the tariff the coalition succeeds in curbing the fringe countries' fuel consumption, the more so, the larger the coalition. Therefore, the tariff is an effective instrument for diminishing the fringe countries' free-rider advantage. Figure 2b depicts the effective consumer prices of fuel[19] for fringe and coalition countries in the scenarios with and without tariffs. These prices are regulated in such a way that they keep the fuel demand (= emission supply) equal to the emission cap, as required by (7). The curvatures are as expected: Increasing consumer prices (p_{co}, p_{ct}) corresponds to decreasing caps (e_{co}, e_{ct}), the strongly decreasing price p_{of} corresponds to strongly increasing cap e_{fo} and the slightly increasing cap e_{ft} is associated with a slightly decreasing price p_{ft}. At first glance there seems to be a degree of freedom regarding the choice of t and π, since it is only the sum $t+\pi$ that matters for (7). But that degree of freedom is used up by the tariff design which requires applying the same tariff rate to the producer price of fuel.

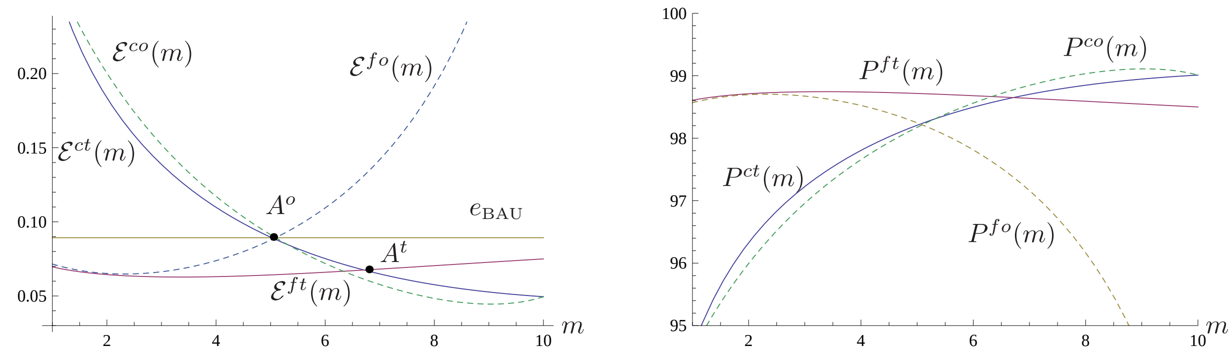

Figure 2a

Figure 2b

Figure 2: Country emission caps (Fig. 2a) and consumer prices of fuel (Fig. 2b)
$[\mathcal{P}^{kz}(m) := \mathcal{P}^{z}(m) + \Pi^{kz}(m) + \mathcal{T}^{k}(m);\ k = c, f;\ z = o, t]$

Two highly remarkable properties of the graphs of $\mathcal{T}^c$ and $\mathcal{T}^f$ can be observed in Figure 3b. First, the tariff t_c and t_f are negative for all m such that fuel production is taxed and fuel consumption is subsidized in coalition countries as well as in the fringe. Second, while $|t_f|$ is small and varies with m only slightly,[20] $|t_c|$ increases strongly with the coalition size. The negativity and large absolute size of the coalition countries' tariff is striking, because for all m these countries turn out to import fuel (as shown in Figure 5a below). One could have expected the coalition to set positive tariff rates to improve its terms of trade. Instead,

[19] See footnote 11 above.

[20] These features suggest that the results would not differ markedly in a scenario (not studied here) in which tariffs are only levied by the coalition but not by fringe countries.

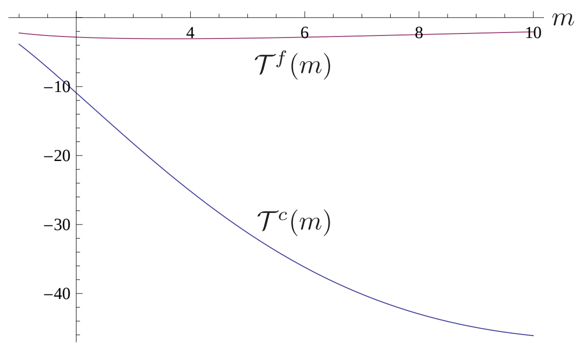

Figure 3: Tariff rates

the tariffs raise the fringe countries' consumer price of fuel which in turn induces the fringe countries to reduce their fuel consumption compared to the case without tariffs.

If tariffs are not imposed, production is uniform across countries ($\mathcal{E}^{sco}(m) = \mathcal{E}^{sfo}(m) = \mathcal{E}^{so}(m)$) and decreasing in the coalition size (Figure 4a). That decline of fuel production with m is brought about by the shrinking producer price of fuel, p_o, in Figure 4b. In stark contrast to the uniformly decreasing fuel production in the absence of tariffs, with tariffs the fringe countries slightly increase their fuel production with m, while coalition countries reduce their fuel supply significantly below BAU level. The fuel supplies are determined, of course, by the producer prices of fuel, $\mathcal{P}^t(m) + \mathcal{T}^k(m)$ for $k = c, f$ plotted in Figure 4b. Therefore $\mathcal{E}^{sct}(m) < \mathcal{E}^{sft}(m)$ in Figure 4a follows from $\mathcal{T}^c(m) < \mathcal{T}^f(m) < 0$ for all m in Figure 3b.

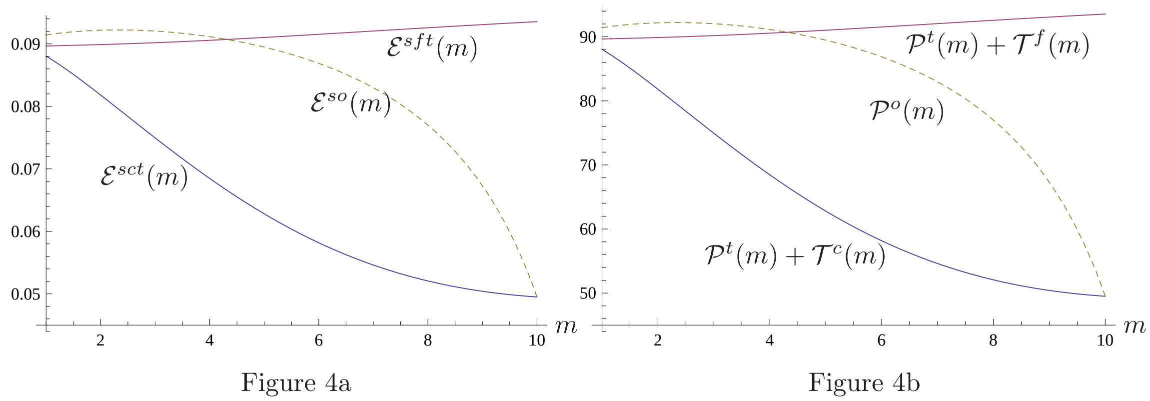

Figure 4: Country fuel supplies (Fig. 4a) and producer prices of fuel (Fig. 4b)

Next we combine the information contained in the Figures 2a and 4a to determine the excess demands for fuel in coalition and fringe countries (Figure 5). From $\mathcal{E}^{sct}(m) < \mathcal{E}^{sft}(m)$ for all m it is clear that in case of tariffs coalition countries import fuel and fringe countries export fuel for all m. The fuel exports of a fringe country vary only slightly with m, while the imports of a coalition country are large for small m and diminish with increasing m. The trade patterns are quite different in the absence of tariffs. In that case there is a coalition size $\tilde{m} = 4.88$ for which net trade flows are zero and coalition countries import [export] fuel, if and only if $m > \tilde{m}$ [$m < \tilde{m}$].[21]

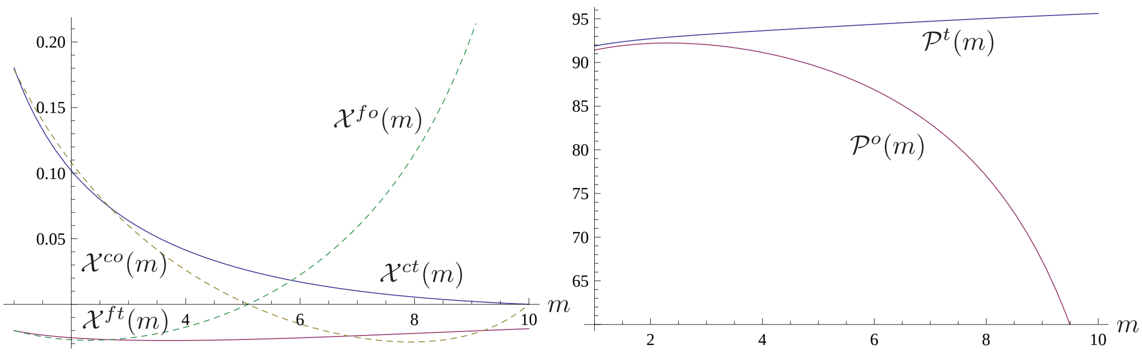

Figure 5a Figure 5b

Figure 5: Fuel exports and imports (Fig. 5a) and world fuel prices (Fig. 5b)
$[\mathcal{X}^{kz}(m) := \mathcal{E}^{kz}(m) - \mathcal{E}^{skz}(m);\ k = c, f;\ z = o, t]$

We have discussed above the impact of coalitions of alternative size on the reduction of total emissions (compared to BAU emissions) and how the outcome differs when governments have at their disposal cap-and-trade schemes and tariffs. Now we complement that analysis by addressing its welfare implications by means of the Figures 6 and 7.

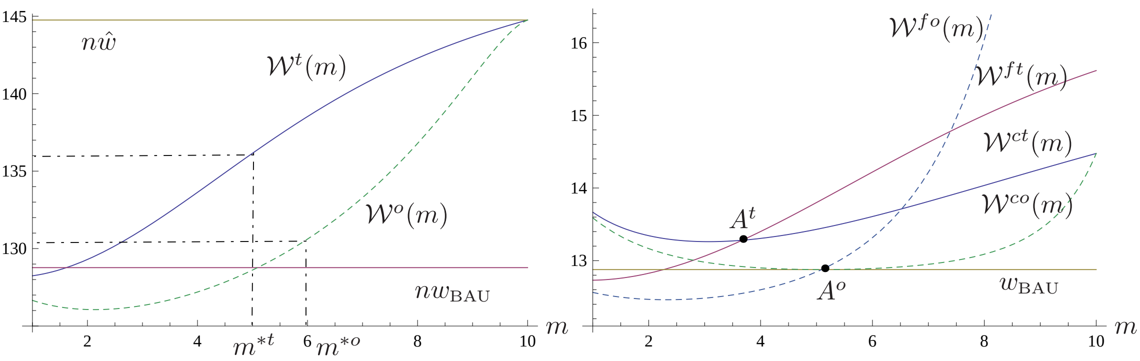

Figure 6a Figure 6b

Figure 6: World welfare (Fig. 6a) and country welfare (Fig. 6b)
$\left[\mathcal{W}^{z}(m) := m\mathcal{W}^{cz}(m) + (n-m)\mathcal{W}^{fz}(m);\ z = o, t\right]$

The important message of Figure 6a is that for all $m \in \{1, \ldots, n-1\}$ the world welfare is significantly higher with tariffs than without.[22] Figure 6b compares the welfare of coalition and fringe countries which will turn out to be crucial for the issue of coalition stability in the next section. To describe the curvature of the countries' welfare functions in Figure 6b,

[21] For more details see Eichner and Pethig (2013).

[22] An obvious qualification is that for large m the positive difference $\mathcal{W}^{t}(m) - \mathcal{W}^{o}(m)$ tends to zero if m approaches n. Note also that without tariffs at small coalition sizes the world welfare is lower than in BAU. For details see Eichner and Pethig (2013).

it is convenient to denote by $m(A^t)$ and $m(A^o)$ the coalition sizes associated to the points A^t and A^o, respectively. With this notation, it is obvious from Figure 6b that

$$\mathcal{W}^{cz}(m) - \mathcal{W}^{fz}(m) \gtreqqless 0 \quad \Longleftrightarrow \quad m \lesseqqgtr m(A^z) \quad \text{for } z = o, t.$$

Apart from that similarity, the scenarios with and without tariffs exhibit important differences. First, for all $m \in \{1, \ldots, n-1\}$ the welfare of coalition countries is strictly higher with tariffs than without. That implies, in particular, that the welfare of coalition countries is always above BAU level. Second, the welfare of fringe countries is higher with tariffs than without for all m smaller than some (rather high) threshold value beyond which the reverse ranking holds. That switch occurs, because the (positive) difference $\mathcal{W}^{fo}(m) - \mathcal{W}^{co}(m)$ increases with m on the interval $[m(A^o), n[$ much faster than the (positive) difference $\mathcal{W}^{ft}(m) - \mathcal{W}^{ct}(m)$ on the interval $[m(A^t), n[$. Economically speaking, increasing m boosts the free rider advantage much less with tariffs than without.

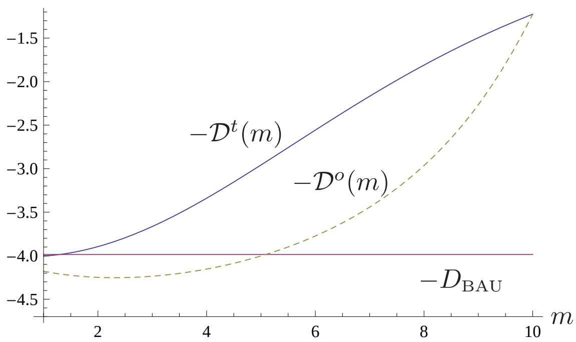

Figure 7a

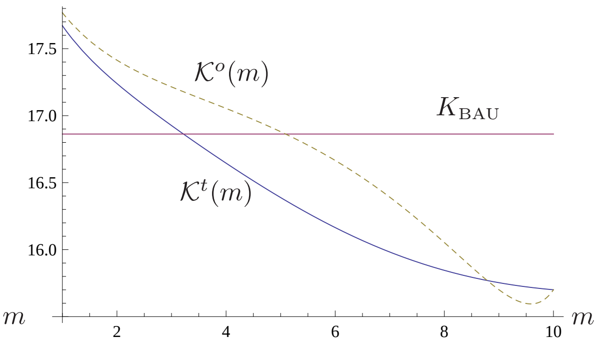

Figure 7b

Figure 7: Climate welfare (Fig. 7a) and consumption welfare (Fig. 7b) of coalition countries

The determinants of the positive difference $\mathcal{W}^{ct}(m) - \mathcal{W}^{co}(m)$ can be readily identified in Figure 7. Figure 7a shows that with and without tariffs the climate welfare (= climate damage $\mathcal{D}^z(m)$ multiplied by minus one) increases with m, because total emissions decrease with m (Figure 1). However the climate welfare with tariffs is higher than without. In contrast, according to Figure 7b the difference $\mathcal{K}^t(m) - \mathcal{K}^o(m)$ is negative except for very large coalitions, where $\mathcal{K}^z(m) := \mathcal{W}^{cz}(m) + \mathcal{D}^z(m)$ is the consumption welfare of coalition countries. Hence in all coalitions except very large ones, coalition countries suffer a consumption welfare loss compared to BAU but their climate welfare enhances, and the latter gain overcompensates the former loss. To put it differently, in case of tariffs coalitions (of given size) find it advantageous to sacrifice more consumption than in BAU to mitigate climate damage. They do so for the benefit of enhanced climate welfare, and this procedure results in $\mathcal{W}^{ct}(m) > \mathcal{W}^{co}(m)$.

4 Self-enforcing IEAs

In the preceding Section 3 we have presupposed the existence of a climate coalition, and our focus has been on characterizing the Stackelberg equilibrium and its dependence on the exogenous coalition sizes $m \in [0, n]$. Now we turn to the issue of coalition stability. Under the realistic assumption that supranational authorities for the effective enforcement of agreements are not available, IEAs will not prevail unless they are self-enforcing in the sense that no signatory has an incentive to defect (internal stability) and no non-signatory has an incentive to sign the agreement (external stability).[23] In formal language, an IEA with $m \in \{1, \ldots, n\}$ signatories is said to be self-enforcing or stable, if it satisfies the internal stability condition

$$\mathcal{W}^c(m) \geq \mathcal{W}^f(m-1) \tag{19}$$

and the external stability condition

$$\mathcal{W}^f(m) \geq \mathcal{W}^c(m+1). \tag{20}$$

Closer inspection of the curvature of the graphs of $\mathcal{W}^{cz}$ and $\mathcal{W}^{fz}, z = o, t$ in Figure 6b reveals that if a self-enforcing IEA with $m^{*z} \in \{1, \ldots, n\}$ signatories exists, then $m^{*z} > m(A^z)$. To verify that claim for the case[24] $z = t$, note that the external stability condition (20) is violated for all $m \in \{1, \ldots, n\}$ satisfying $m < m(A^t)$, because $\mathcal{W}^{ft}_m(m) > 0$ and $\mathcal{W}^{ct}(m) > \mathcal{W}^{ft}(m)$ for all $m < m(A^t)$. If $m(A^t)$ happens to be an integer, the coalition of size $m(A^t)$ is not stable either, because fringe countries have still an incentive to join the coalition ($\mathcal{W}^{ft}[m(A^t)] < \mathcal{W}^{ct}[m(A^t)+1]$). The information that "$m^{*t} > m(A^t)$, if m^{*t} exists" is important but not very deep, because it leaves open whether m^{*t} exists, and if so, how large the positive difference $[m^{*t} - m(A^t)]$ is. Unfortunately, the complexity of the functions $\mathcal{W}^{ft}$ and $\mathcal{W}^{ct}$ prevents answering the existence question analytically. We therefore resort to examining the stability conditions (19) and (20) for the numerical example underlying the Figures 1 through 7. The result is illustrated in Figure 8 that presents the graphs of the functions $\mathcal{W}^{cz}(m) - \mathcal{W}^{fz}(m-1)$ and $\mathcal{W}^{fz}(m) - \mathcal{W}^{cz}(m+1)$ for $z = t$ (Figure 8a) and for $z = o$ (Figure 8b).

In both panels of Figure 8 there is one and only one interval of coalition sizes in which both functions take on non-negative values thus satisfying (19) as well as (20). That

[23]This notion of self-enforcement or stability was originally introduced by D'Aspremont et al. (1983) in the context of cartel formation.

[24]For the other case see Eichner and Pethig (2013).

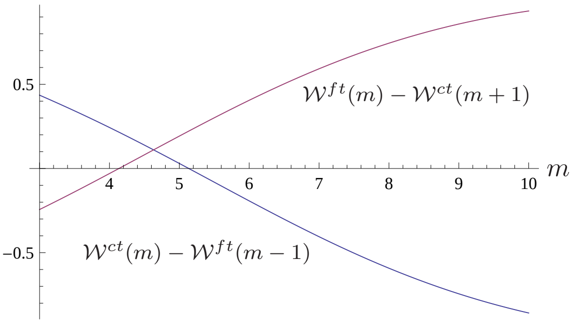

Figure 8a

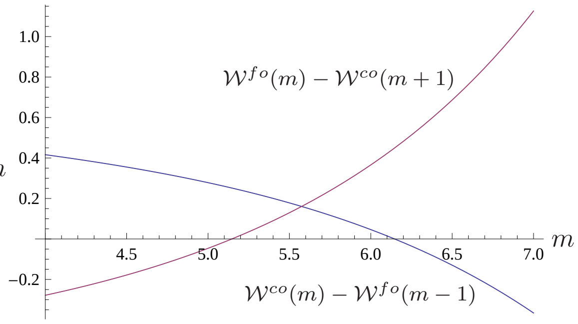

Figure 8b

Figure 8: Coalition stability when fuel taxes are (Fig. 8a) are or are not (Fig. 8b) at the governments' disposal

interval contains one and only one integer, $m^{*t} = 5$ in Figure 8a and $m^{*o} = 6$ in Figure 8b. According to Figure 8, m^{*z} is the smallest integer larger than $m(A^z)$ for $z = o, t$.[25] We take this information to identify in the Figures 1 - 7 the values of the variables which prevail in a Stackelberg equilibrium *with a stable coalition* of size m^{*z}, $z = o, t$ and summarize the comparison as follows.

Result 2. *As above, consider the example specified by the parameters* $a = 100$, $b = 20$, $\bar{x} = 12$, $\alpha = 1000$, $\delta = 10$ *and* $n = 10$.[26]

(i) Without tariffs, the caps of coalition countries are tighter than BAU emission caps which are in turn tighter than emission caps of fringe countries. With tariffs, the caps of the fringe countries are tighter than those of coalition countries, and all caps are below BAU emissions: $\mathcal{E}^{fo}(m^{*o}) > e_{BAU} > \mathcal{E}^{ct}(m^{*t}) > \mathcal{E}^{co}(m^{*o}) > \mathcal{E}^{ft}(m^{*t})$.

(ii) With tariffs, the fuel production of fringe countries is higher than that of coalition countries. The former is above and the latter is below the uniform level of fuel production without tariffs: $\mathcal{E}^{fst}(m^{*t}) > \mathcal{E}^{cso}(m^{*o}) = \mathcal{E}^{fso}(m^{*o}) > \mathcal{E}^{cst}(m^{*t})$.

(iii) Without tariffs, fringe countries import and coalition countries export fuel. With tariffs, the trade flows are reversed: $[\mathcal{E}^{fo}(m^{*o}) - \mathcal{E}^{fso}(m^{*o})] > 0 > [\mathcal{E}^{co}(m^{*o}) - \mathcal{E}^{cso}(m^{*o})]$ *and* $[\mathcal{E}^{ct}(m^{*t}) - \mathcal{E}^{cst}(m^{*t})] > 0 > [\mathcal{E}^{ft}(m^{*t}) - \mathcal{E}^{fst}(m^{*t})]$.

[25] Eichner and Pethig (2013) show for a large number of examples that the size m^{*o} of the unique self-enforcing IEA is the smallest or second smallest integer larger than the coalition size $\tilde{m}$ defined by $\mathcal{W}^{co}(\tilde{m}) = \mathcal{W}^{fo}(\tilde{m})$. In Figure 6b we have $\tilde{m} = m(A^o)$. In the model without tariffs, the allocation of Stackelberg equilibria with self-enforcing IEAs is approximately the same as in BAU. We conjecture that m^{*t} is also always close to the coalition size $\check{m}$ defined by $\mathcal{W}^{ct}(\check{m}) = \mathcal{W}^{ft}(\check{m})$. But in case of tariffs the allocation associated to m^{*t} differs markedly from BAU as will be discussed below.

[26] In the variations of Example 2 - to be presented below - we find the ranking $\mathcal{E}^{ct}(m^{*t}) > \mathcal{E}^{fo}(m^{*o}) > e_{\mathrm{BAU}} > \mathcal{E}^{co}(m^{*o}) > \mathcal{E}^{ft}(m^{*t})$. The rankings of Result 2(ii)-(iv) hold for all examples of Tables 1 - 4.

(iv) *With and without tariffs, fringe countries enjoy a higher level of welfare than coalition countries and all welfare levels are higher than the (uniform) welfare levels in BAU. With tariffs, all countries' welfare levels are higher than without:* $\mathcal{W}^{ft}(m^{*t}) > \mathcal{W}^{ct}(m^{*t}) > \mathcal{W}^{fo}(m^{*o}) > \mathcal{W}^{co}(m^{*o}) > w_{BAU}$.

Next we wish to make precise the degree by which the regulation with emission trading and tariffs is more effective in fighting climate change than the stand-alone cap regulation. To that end we consider the following effectiveness indicators:

$$\mathrm{RE}^z := \frac{ne_{\mathrm{BAU}} - \left[m^{cz}\mathcal{E}^{cz}(m^{*z}) + (n - m^{*z})\mathcal{E}^{fz}(m^{z*})\right]}{ne_{\mathrm{BAU}} - n\hat{e}} \cdot 100, \quad z = o, t, \tag{21}$$

$$\mathrm{RW}^z := \frac{\left[m^{cz}\mathcal{W}^{cz}(m^{*z}) + (n - m^{*z})\mathcal{W}^{fz}(m^{*z})\right] - nw_{\mathrm{BAU}}}{n\hat{w} - nw_{\mathrm{BAU}}} \cdot 100, \quad z = o, t. \tag{22}$$

In (21) $ne_{\mathrm{BAU}} - n\hat{e}$ is the gap between total emissions in BAU, ne_{BAU}, and total emissions in the social optimum, $n\hat{e}$, and hence measures the absolute magnitude of excess emissions in BAU. We call $ne_{\mathrm{BAU}} - n\hat{e}$ the emission gap, for short. In (22) $n\hat{w} - nw_{\mathrm{BAU}}$ is the gap between global welfare in the social optimum, $n\hat{w}$, and global welfare in BAU, nw_{BAU}, and hence measures the absolute magnitude of the global welfare loss in BAU. We call $n\hat{w} - nw_{\mathrm{BAU}}$ the welfare gap, for short. Since the emission gap and the welfare gap are independent of regulation with and without tariffs, we use them in (21) respectively (22) as a benchmark in both policy scenarios. The indicators RE^z and RW^z measure the fraction of the emission gap and welfare gap, respectively, which the self-enforcing IEA succeeds to close. To put it differently, RE^z and RW^z, $z = o, t$, are indicators for the effectiveness of climate change mitigation (or of the internalization of climate damage) through coalition formation.[27] For the example underlying the Figures 1 - 8 we find $\mathrm{RE}^o = 6.05\%$, $\mathrm{RE}^t = 31.11\%$, $\mathrm{RW}^o = 11.52\%$ and $\mathrm{RW}^t = 46.20\%$. These numbers imply $\mathrm{RE}^t = 5.14 \cdot \mathrm{RE}^o$ and $\mathrm{RW}^t = 4.01 \cdot \mathrm{RW}^o$ which gives rise to

Result 3. *In the example specified by the parameters* $a = 100$, $b = 20$, $\bar{x} = 12$, $\alpha = 1000$, $\delta = 10$ *and* $n = 10$ *regulation with emission caps and tariffs compared to stand-alone emission cap regulation enhances the effectiveness of fighting climate change by the factor 5 regarding excess emissions and by 4 regarding the global welfare loss.*

The finding that regulation with emission caps and tariffs succeeds in internalizing a much larger share of the climate externality than stand-alone emission cap regulation is all the more remarkable as the stable coalition with tariffs is smaller than without ($m^{*t} = 5$ versus $m^{*o} = 6$).

[27] Finus (2003, p. 110) suggests measures similar to RE^z and RW^z which he denotes measures of the 'degree of externality'.

So far our characterization of the stable coalition rests on one numerical example only. We now proceed investigating how robust our findings are, i.e. how parameter variations affect the outcome. In numerous simulations, many more than reported here, the results turned out to be particularly sensitive with respect to the size of the parameters α and δ. Therefore, we compute two further examples, the Examples 1 and 2,[28] and vary their parameters α and δ, one at a time. The outcome of the Example 1 is presented in the 3rd column of Table 1 and in the 3rd column of Table 3. The 1st column of Table 2 and the 3rd column of Table 4 contain the outcome of Example 2. In addition, the Tables 1 - 4 list the results of a number of other simulations based on parameter constellations that differ from the Examples 1 and 2 only with respect to either the parameter α or the parameter δ.

	a	α	b	δ	n
Example 1	100	1000	20	1	10
Example 2	100000	500000	100	1	50

Before we enter into a discussion and interpretation of each table, it is useful to comment on their common features. The 1st row of all tables shows that the emission gap (e-gap $= ne_{\text{BAU}} - n\hat{e}$) increases in the order of the columns from the first column upward. The gap increases with increasing δ in the Tables 1 and 2 and it increases with decreasing α in the Tables 3 and 4. The effect of α on the emission gap is easy to see from observing that $C(e_i^s, \alpha) := T(0) - T(e_i^s) = \frac{\alpha}{2}(e_i^s)^2$ are the fuel extraction costs, expressed in units of good X. These extraction costs are obviously progressively increasing in output, and decreasing α corresponds to declining marginal and total extraction costs. Thus decreasing α renders fossil fuel relatively more abundant which drives fuel consumption and emissions up and thus increases the emission gap. The impact of δ is also straightforward, because increasing values of δ render more severe the climate damage for given levels of total emissions and thus exacerbate the climate externality. As expected, the welfare gap (w-gap $= n\hat{w} - nw_{\text{BAU}}$), like the emission gap, also increases in the order of the columns from the first column upward, as the 2nd row of the tables shows. It is worth noting that the increase in the welfare gap caused by decreasing α or increasing δ is much more progressive than the increase in the emission gap. Another common feature of the Tables 1 - 4 is that the rows 3, 4 and 5 list the stable coalition size and the indicators RE and RW for the model without tariffs while the remaining rows 6, 7 and 8 present the same information for the model with tariffs. Rows 9 and 10 list the factors by which the stable coalition with tariffs is more effective to close

[28] A natural way to proceed would have been to take the example of Section 3 as the base for further simulations. The only reason for our deviation is the requirement to secure positive emissions in all equilibrium allocations. We have observed that constraint in all other examples listed in the Tables 1 - 4 as well. Note also that the 5th column in Table 1 contains the example of Section 3.

the emission gap and the welfare gap, respectively, compared to the stable coalition without tariffs.

δ		0.01	0.5	1	5	10	20	30
e -gap	1	0.001	0.041	0.078	0.276	0.398	0.488	0.508
w-gap	2	0.0001	0.09	0.34	0.41	15.98	36.04	52.04
m^{*o}	3	5	5	5	6	6	6	6
RE^o	4	0.43%	0.41%	0.39%	5.49%	6.05%	6.15%	5.34%
RW^o	5	0.87%	0.82%	0.78%	10.47%	11.52%	11.76%	10.28%
m^{*t}	6	4	4	4	5	5	5	5
RE^t	7	13.34%	13.74%	14.13%	27.52%	31.11%	35.22%	37.02%
RW^t	8	21.81%	22.43%	23.03%	41.50%	46.20%	51.49%	53.84%
$\mathrm{RE}^t/\mathrm{RE}^o$	9	30.65	33.08	36.07	5.01	5.14	5.72	6.93
$\mathrm{RW}^t/\mathrm{RW}^t$	10	25.19	27.13	29.53	3.96	4.01	4.38	5.24

Table 1: Variations of δ in Example 1 (e-gap$= ne_{\mathrm{BAU}} - n\hat{e}$, w-gap$= nw_{\mathrm{BAU}} - n\hat{w}$)

We now turn to the discussion of the Tables 1 and 2 containing the Examples 1 (Table 1) and the Example 2 (Table 2) with variations of the damage parameter δ.

δ		1	10	50	100	200	250	280
e -gap	1	0.049	0.466	1.95	3.23	4.80	5.31	5.56
w-gap	2	11.94	1140	23758	78414	230663	317252	370916
m^{*o}	3	26	26	26	26	26	26	26
RE^o	4	0.134%	0.142%	0.158%	0.174%	0.191%	0.192%	0.191%
RW^o	5	0.276%	0.284%	0.316%	0.348%	0.381%	0.384%	0.381%
m^{*t}	6	12	12	12	12	12	12	12
RE^t	7	5.41%	5.62%	6.53%	7.61%	9.58%	10.47%	10.99%
RW^t	8	9.59%	9.96%	11.53%	13.37%	16.70%	18.20%	19.05%
$\mathrm{RE}^t/\mathrm{RE}^o$	9	39.22	39.57	41.26	43.71	50.14	54.44	57.51
$\mathrm{RW}^t/\mathrm{RW}^t$	10	34.80	35.08	36.44	38.44	43.76	47.35	49.92

Table 2: Variations of δ in Example 2

Table 1: All coalitions[29] comprise of 40% - 60% of all countries and hence are larger than in the basic model of the literature. Without tariffs their size rises with increasing δ

[29]Since we deal with stable coalitions exclusively in all tables we omit the word 'stable' in the following.

from 5 to 6 members and with tariffs from 4 to 5 members. It is remarkable that although the coalitions with tariffs consist of one member less than without tariffs (which corresponds to a significant *relative* difference) their effectiveness measured by RE^t and RW^t is significantly higher than in case without tariffs. When the climate damage is severe, about 10% of the welfare gap is closed without tariffs, but about 40% up to 53% with tariffs.

Table 2: The transition from Table 1 to Example 2 with variations of δ in Table 2 reveals similar patterns but also differences between both tables. First, while in Table 2 coalition sizes are still relatively large and invariant without tariffs (52%), the coalitions are less than half as large in the model with tariffs. Surprisingly, without tariffs the coalitions' effectiveness is below 1% for all values of δ, so that those coalitions hardly improve upon BAU in spite of their impressive size.[30] Compared to Table 1 the relative coalition size with tariffs drops sharply in Table 2. Nonetheless, the coalitions' effectiveness is still greater with tariffs than without by factors exceeding 35. It must be acknowledged, however, that while in Table 1 the coalitions with tariffs are capable to close up to 53% of the welfare gap, in Table 2 they achieve only 19% at most.

Next we consider the variations of the extraction-cost parameter α in the Examples 1 and 2.

α		10000	2000	1000	500	100	50	10
e -gap	1	0.0009	0.02	0.08	0.27	3.14	6.62	17.31
w-gap	2	0.0004	0.05	0.34	2.32	108.93	372.24	1947.12
m^{*o}	3	6	6	5	5	4	3	3
RE^o	4	3.13%	3.84%	0.39%	1.49%	2.86%	1.39%	8.63%
RW^o	5	6.16%	7.45%	0.78%	2.91%	5.43%	2.71%	15.55%
m^{*t}	6	5	5	4	4	4	3	3
RE^t	7	22.35%	22.86%	14.13%	14.87%	19.14%	11.21%	13.83%
RW^t	8	34.70%	35.26%	23.03%	24.03%	30.47%	19.00%	23.69%
$\mathrm{RE}^t/\mathrm{RE}^o$	9	7.13	5.95	36.07	10.00	6.69	8.06	1.60
$\mathrm{RW}^t/\mathrm{RW}^t$	10	5.64	4.73	29.53	8.25	5.62	7.01	1.52

Table 3: Variations of α in Example 1

[30]This is in line with Eichner and Pethig (2013) whose examples consistently show that without tariffs all stable coalitions perform very close to BAU. That result is the more pronounced, the larger the total number of countries, because the relative effect of moving from one integer to the next becomes smaller with increasing n. The 'integer problem' also explains the lack of monotonicity in the rows 4 and 5 of the Tables 1 - 4.

Table 3. Recall that decreasing α exacerbates the climate externality and widens the emission and welfare gaps. According to Table 3 the coalition size is in the range of 3 to 6 and weakly increases in α. Thus with declining α the coalition tends to become smaller while the emission and welfare gaps get larger. In that respect the variations of α and δ differ, because increasing δ results in non-decreasing coalition sizes and increasing emission and welfare gaps. In Table 3 coalition sizes are either the same in both policy scenarios or are smaller by one member with tariffs than without. But despite their slight disadvantage in coalition size the coalitions with tariffs are always more effective than without. However, the extent of the effectiveness advantage of coalitions with tariffs differs strongly and changes non-monotonely in the size of α. The effectiveness advantage may be very small, e.g. for $\alpha = 10$ (column 7 of Table 3) in which case the emission and welfare gaps are large. In other cases the lead in effectiveness of coalitions with tariffs is significant, e.g. for $\alpha = 1000$ (column 3 of Table 3).

α		10^7	10^6	500000	100000	50000	10000	1500
e -gap	1	0.0001	0.012	0.049	1.19	4.64	95.78	1810
w-gap	2	0.0015	1.496	11.94	1458	11343	$1.16 \cdot 10^6$	$1.34 \cdot 10^8$
m^{*o}	3	26	26	26	25	25	21	11
RE^o	4	0.120%	0.128%	0.138%	0.051%	0.139%	0.080%	0.116%
RW^o	5	0.239%	0.257%	0.276%	0.103%	0.276%	0.159%	0.229%
m^{*t}	6	12	12	12	11	11	9	5
RE^t	7	5.39%	5.40%	5.41%	4.59%	4.69%	3.59%	1.92%
RW^t	8	9.57%	9.58%	9.59%	8.17%	8.30%	6.37%	3.56%
RE^t/RE^o	9	45.03	42.07	39.22	88.69	33.82	44.71	16.58
RW^t/RW^t	10	39.99	37.34	34.80	78.99	30.04	39.89	15.52

Table 4: Variations of α in Example 2

Table 4. Table 4 supplements Table 3 by presenting variations of α based on Example 2. Similar as in Table 3, with declining α the coalition tends to become smaller while the corresponding emission and welfare gaps get larger. But different from Table 3 and similar as in Table 2, the coalitions with tariffs are only less than half as large as without tariffs. That feature suggests that it is the increase in the total number of countries (here from $n = 10$ to $n = 50$) which reduces the size of coalitions with tariffs relative to their size without tariffs. Moreover, increasing the total number of countries also appears to make coalitions less effective. In the case without tariffs, the effectiveness rates are consistently below one percent confirming the results in Table 2. Coalitions with tariffs also achieve

rather small effectiveness rates roughly ranging from 2 to 10 percent. However, the values of the effectiveness indicators RE^t and RW^t are still larger by factors greater than 15 than the corresponding values of RE^o and RW^o.

We are aware that we cannot draw 'general' conclusions from the simulations in the Tables 1 - 4. Nonetheless, these tables suggest

Result 4 .

(i) *In the scenario without tariffs the results of Eichner and Pethig (2013) are reconfirmed. Stable coalitions may be quite large but they are not very effective with regard to closing the emission and welfare gaps (independent of whether they are large or small). Their effectiveness performance appears to be slightly better when the total number of countries is small, but in general they perform almost as in business as usual.*

(ii) *Compared to the scenario without tariffs the use of tariffs (in addition to emission trading) improves the effectiveness of stable coalitions. The degree of improvement varies with the parameter constellations chosen.*[31]

(iii) *The stable size of coalitions with tariffs is at most as large as without tariffs and may be even less than half as large as the size of coalitions without tariffs. Nonetheless, in terms of effectiveness all (smaller) coalitions with tariffs outperformed the (larger) coalitions without tariffs.*

(iv) *Suppose the emission and welfare gaps widen because, ceteris paribus, the climate damage becomes successively more severe ($\delta \uparrow$). Then the size of stable coalitions does not decrease and the effectiveness indicators RE^z and RW^z, $z = o, t$, tend to increase.*[32]

(v) *Suppose the emission and welfare gaps widen because, ceteris paribus, the extraction costs successively decline ($\alpha \downarrow$). Then the size of stable coalitions weakly decreases and the effectiveness indicators RE^z and RW^z, $z = o, t$, vary in a non-monotone way.*

It is interesting to compare these findings with the literature on self-enforcing IEAs. With reference to Barrett (1994) Finus (2003, p. 111) argues that "... whenever the gap between first- and third-best is large this is also true for the gap between first- and second-best and vice versa ...". We identify the gap between the first- and third-best with the welfare gap $n\hat{w} - nw_{\text{BAU}}$ and consider the total welfare in the Stackelberg equilibrium with a stable coalition, i.e. $(n - m^{*z})\mathcal{W}^{fz}(m^{*z}) + m^{cz}\mathcal{W}^{cz}(m^{*z})$, $z = o, t$, to be the second-best. Then we

[31] In our examples we found the effectiveness indicator RE^t [RW^t] to be larger than RE^o [RW^o] by factors between 1.6 [1.5] and 88.7 [79.0] for variations in α, and by factors between 5.0 [4.0] and 57.5 [49.9] for variations in δ.

[32] The increase is not monotone in all cases. See also footnote 3.

translate our quote from Finus into the statement: The larger the welfare gap, the smaller is the effectiveness indicator RW^z, $z = o, t$. Our Result 4(iv) above is at variance with that statement. Moreover, Karp and Simon (2012) summarize the results of the literature on IEAs as follows: "... the equilibrium size of a stable IEA is small except when the potential gains from cooperation are also small". If we identify the 'potential gains from cooperation' with the welfare gap that statement is true for variations in α (Tables 3 and 4), but not for variations in δ (Tables 1 and 2).

5 On the role of the tariff

In conventional trade models of large countries without market imperfections, an 'optimal tariff' is a unilateral import tariff, i.e. a tax on imports, that enhances the country's welfare through improving its terms of trade, curbing imports and sheltering domestic production (e.g. Johnson 1953-1954, Kuga 1973). However, each country has an incentive to improve its terms-of-trade via an import tariff such that with retaliation all countries set inefficiently high tariffs in the resultant non-cooperative Nash equilibrium. All these tariffs cause international terms-of-trade externalities which can be internalized by trade negotiations (e.g. WTO negotiations, see Bagwell and Staiger 1999). In our model, the analogue of such import tariffs would be positive tariff rates t_c and t_f. In stark contrast, all our simulations showed that the tariff rates are negative for fringe countries as well as for the coalition which amounts to subsidizing consumption and taxing production of fuel. Since the coalition imports fuel, its tariff is a subsidy on imports and the fringe countries' tariff is a tax on exports.

In order to better understand that intriguing and counterintuitive result, we take as our point of departure the Stackelberg equilibrium $(s_c^*, s_f^*, t_c^*, t_f^*)$ for some coalition size m and consider the welfare functions W^{c*} and W^{f*} defined by

$$W^{k*}(t_c; s_c^*) := W^k[s_c^*, t_c, R^\sigma(s_c^*, t_c; m), R^\tau(s_c^*, t_c; m); m], \quad k = c, f. \tag{23}$$

In (23) we have fixed the coalition's aggregate emissions at their optimal level s_c^*, and let the coalition vary its tariff rate t_c. Figure 9a plots the graphs of W^{c*} and W^{f*} for Example 1 with $m = 4$. It shows that W^{c*} as well as W^{f*} are strictly decreasing[33] for all $t_c > t_c^*$. Hence lowering successively the rate t_c from positive to negative is not only beneficial for the coalition but also for the fringe countries. This is so for the following reasons. First, owing to $R^\sigma_{t_c} > 0$ the fringe reacts to smaller rates t_c by reducing emissions s_f. That

[33]Figure 9a also shows that W^{c*} is strictly concave in t_c and attains its maximum at $t_c = t_c^*$.

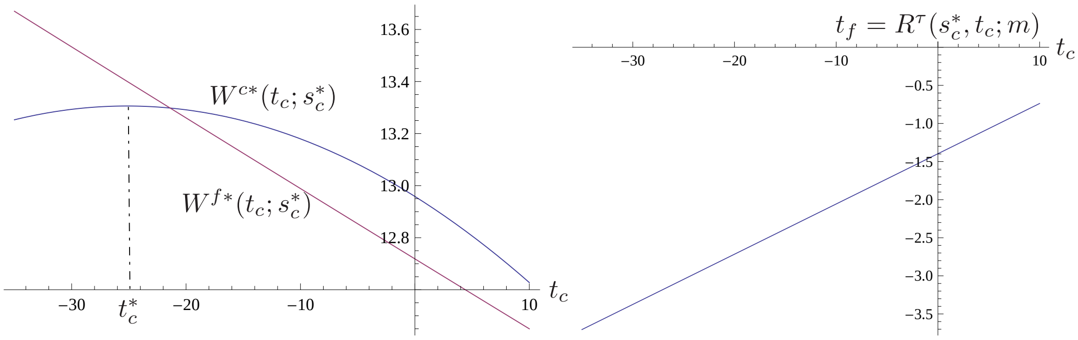

Figure 9a

Figure 9b

Figure 9: The welfare functions W^{k*}; $k = c, f$ (Fig. 9a) and the fringe's reaction (Fig. 9b)

lowers the climate damage because $s_c = s_c^*$ by presupposition. In other words, the coalition uses its tariff to lower the leakage rate and thus renders more effective its mitigation efforts. Surprisingly, reducing the leakage rate benefits the fringe countries as well, since their gain in climate welfare overcompensates their loss in consumption welfare. Second, with decreasing t_c the coalition countries' welfare is affected in two ways. Their climate welfare increases (as described above), but their consumption welfare declines, because their consumption of good X shrinks. The latter effect follows from the observation that their terms of trade deteriorate and their producer price of fuel increases (see Appendix C). According to Figure 9a, the gain in climate welfare over-compensates the consumption welfare loss for small absolute values of t_c, but the net welfare gain shrinks with successive reductions in t_c and eventually becomes zero at $t_c = t_c^*$.

To highlight the role of tariffs from another perspective, we find it useful to consider the welfare functions $\tilde{W}^{c*}$ and $\tilde{W}^{f*}$ defined by

$$\tilde{W}^{k*}(t_c; s_c^*, s_f^*) := W^k \left[s_c^*, t_c, s_f^*, R^\tau(s_c^*, t_c; m); m\right], \quad k = c, f. \tag{24}$$

Our thought experiment associated with (24) is to fix the emissions (s_c, s_f) at their equilibrium levels (s_c^*, s_f^*) and let the coalition vary the tariff rate t_c. The coalition accounts for the reaction $t_f = R^\tau(s_c^*, t_c; m)$ of fringe countries, as before, but it also knows that the reaction $s_f = R^\tau(s_c^*, t_c; m)$ is now replaced by $s_f = s_f^*$. The fixed fringe emissions bar the coalition from using its tariff to diminish the leakage rate. It does not follow, however, that under these conditions the coalition's best choice is $t_c = 0$. Instead, according to Figure 10a the coalition's welfare-maximizing tariff rate is positive, and the associated tariff rate of the fringe is negative, as illustrated in Figure 10b. Since fixing (s_c^*, s_f^*) excludes climate damage variations, the positive welfare gains, $\tilde{W}^{c*}(t_c; s_c^*, s_f^*) - \tilde{W}^{c*}(t_c = 0; s_c^*, s_f^*) > 0$, for some $t_c > 0$ are a consequence of the second-best nature of the scenario under review. The 'artificially' introduced quantitative constraint $(s_c, s_f) = (s_c^*, s_f^*)$ causes allocative distortions and creates a second-best scenario. The tariff rates t_c and $t_f = R^\tau(s_c^*, t_c; m)$ introduce additional distortions. But the coalition is able to fix t_c such that its net consumption welfare loss from both distortions is minimized. That minimum is achieved at a positive rate t_c under the conditions of equations (24). More specifically, the coalition imposes the (positive) import tariff to reduce the world market price of fossil fuel which in turn reduces its import bill, enhances its income and hence increases the coalition's consumption of good X.

The thought experiments associated with the equations (23) and (24) differ from each other in that $s_f = R^\sigma(s_c^*, t_c; m)$ holds in the former and is replaced by $s_f = s_f^*$ in the latter. The comparison shows that if the coalition has the opportunity to influence the emission of the fringe via its tariff rate (scenario of equation (23)), it chooses a negative rate giving priority to reducing the leakage rate. Otherwise, i.e. in the scenario of equation (24), it chooses a positive rate.

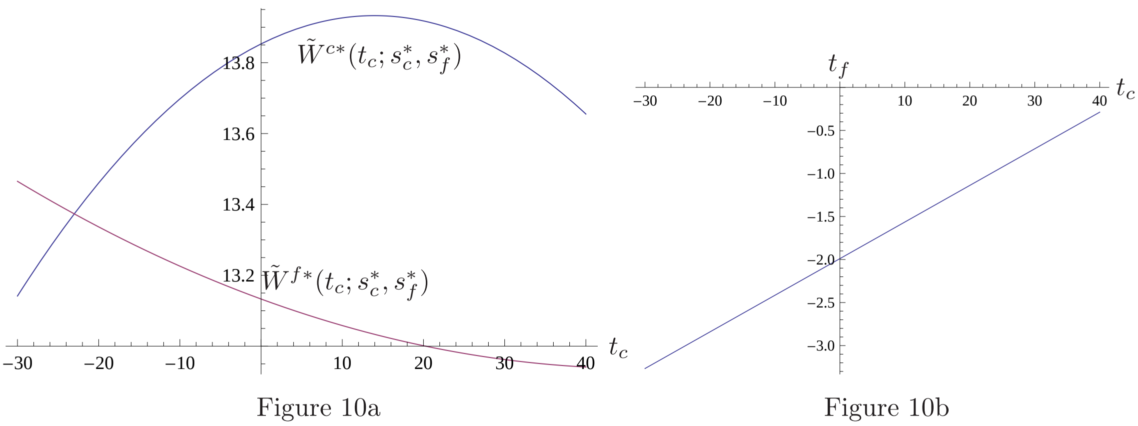

Figure 10: The welfare functions $\tilde{W}^{k*}$; $k = c, f$ (Fig. 10a) and the fringe's reaction (Fig. 10b)

6 Concluding remarks

This paper addresses the role of trade tariffs for the formation of self-enforcing IEAs in the basic model of the IEA literature (Barrett 1994; Rubio and Ulph 2006) extended by consumption and production of a composite consumer good, fossil fuel and trade (Eichner and Pethig 2013). The central question is whether tariffs are capable to enhance the size and/or performance of stable coalitions. Assuming that signatories act as Stackelberg leader and restricting our attention to positive emissions we find

(i) that tariffs reduces the size of stable IEAs,

(ii) and that in stable IEAs with tariffs the 'gains of cooperation' are larger than in stable IEAs without tariffs. Compared to the case of global non-cooperation the use of tariffs allows the coalition countries to achieve a welfare gain and a significant climate damage reduction.

In each Stackelberg equilibrium the coalition imports fossil fuel. One would expect that the coalition sets a positive import tariff in order to reduce the international fuel price and its import bill which would increase its member countries' income and consumption welfare. However, this effect is overcompensated by the coalition's endeavour to reduce total emissions and to fight climate change. In fact, the coalition subsidizes rather than taxes fuel imports thus pushing up the world market fuel price. This in turn increases the consumer price of fuel in fringe countries and forces the fringe countries to reduce their fossil fuel consumption and their emissions - compared to the case where the coalition abstains from using the (negative) tariff. To put it differently, for given coalition size the tariff allows the coalition to reduce the leakage rate and to shift some of the burden of emission reduction to fringe countries. In the model with tariffs the fringe countries increase their welfare drastically and the coalition countries increase their welfare moderately compared to the model without tariffs. In summary, there is a good news and a bad news. The bad news is that the size of the stable coalition is smaller with then without tariffs. The good news is that the smaller IEA with tariffs achieves significantly larger total emission reductions and larger total welfare than the larger stable IEA without tariffs.

We concede that it remains an important task to examine the robustness of results. Obviously, assuming identical countries is extremely restrictive. Also, our quasi-linear utility functions abstract from income effects which could modify impact of tariffs on the size and performance of stable IEAs. The principal reason for making use of strong assumptions are tractability and the quest for informative conclusions. Regarding the need for drastic simplifications, our paper is in line with the extant pertaining literature which also copes with real-world and analytical complexities by resorting to simple parametric functional forms and numerical calculations. Further research with less restrictive assumptions - presumably by means of applied computable general equilibrium models - will improve our understanding of the incentives for the formation of self-enforcing IEAs.

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Appendix

Appendix A. Proof of Result 1

Making use of $e_i = e_j =: e_{\text{BAU}}$ and $t_i = t_j =: t_{\text{BAU}}$ for all $i \neq j$ in (13) and (14) we obtain

$$W^i_{e_i} = V'(e_{\text{BAU}}) - \alpha e_{\text{BAU}} + \frac{(n-1)\alpha t_{\text{BAU}}}{n} = 0, \tag{A1}$$

$$W^i_{t_i} = -\frac{t_{\text{BAU}}}{\alpha} + \frac{t_{\text{BAU}}}{\alpha n} = 0. \tag{A2}$$

(A2) immediately implies $t_{\text{BAU}} = 0$, and inserting $V'(e_{\text{BAU}}) = a - be_{\text{BAU}}$ and $D'(ne_{\text{BAU}}) = \delta ne_{\text{BAU}}$ in (A1) establishes $e_{\text{BAU}} = \frac{a}{\alpha+b+\delta n}$. ■

Appendix B. Derivation of the fringe reaction functions

Suppose that country i is a fringe country. Then (13) can be written as

$$\alpha - \frac{bs_f}{n-m} - \frac{\alpha s_f}{(n-m)n} - \frac{(n-1)\alpha(s_c+s_f)}{n^2} + \frac{(n-1)[mt_c+(n-m)t_f]}{n^2} - \delta(s_c+s_f) = 0$$

or, after some rearrangement of terms, as

$$-(n\alpha + n^2 b + \gamma)\cdot s_f + \check{m}^2(n-1)\cdot t_f = \gamma \cdot s_c - m\check{m}(n-1)\cdot t_c - \check{m}n^2 a, \tag{B1}$$

where we write $\gamma := \check{m}[(n-1)\alpha + n^2\delta]$ and $\check{m} := n - m$ for notational convenience.

Correspondingly, (14) is turned into

$$-\frac{t_f}{\alpha} + \frac{mt_c + \check{m}t_f}{\alpha n^2} - \frac{s_c + s_f}{n^2} + \frac{s_f}{\check{m}n} = 0,$$

or equivalently into

$$m\alpha \cdot s_f - \check{m}(n^2 - \check{m})\cdot t_f = \check{m}\alpha \cdot s_c - m\check{m}\cdot t_c. \tag{B2}$$

To solve the equations (B1) and (B2) for s_f and t_f we consider the system of equations

$$\begin{pmatrix} -(n\alpha + n^2 b + \gamma) & \check{m}^2(n-1) \\ m\alpha & -\check{m}(n^2-\check{m}) \end{pmatrix} \cdot \begin{pmatrix} s_f \\ t_f \end{pmatrix} = \begin{pmatrix} \gamma\cdot s_c - m\check{m}(n-1)\cdot t_c - \check{m}n^2 a \\ \check{m}\alpha \cdot s_c - m\check{m}\cdot t_c \end{pmatrix}. \tag{B3}$$

The determinant of (B3) can be written as

$$\begin{aligned} D &:= \check{m}\left\{bn^2(n^2-\check{m}) + \alpha\left[(n^2-\check{m})(n^2-m(n-1)) - m(n-1)\check{m}\right] + \delta n^2(n^2-\check{m})\right\} \\ &= \check{m}n^2\left\{b(n^2-\check{m}) + \alpha\left[\check{m}(n-1)+m\right] + \delta(n^2-\check{m})\right\} = \check{m}n^2\tilde{D} > 0. \end{aligned} \tag{B4}$$

Next we solve (B3) for s_f and t_f:

$$s_f = R^\sigma = \check{m}\left\{-\frac{[(n-1)\alpha + (n^2-\check{m})\delta]}{\tilde{D}}\cdot s_c + \frac{m(n-1)}{\tilde{D}}\cdot t_c + \frac{(n^2-\check{m})a}{\tilde{D}}\right\}, \tag{B5}$$

$$t_f = R^\tau = -\frac{\alpha(\alpha+b+n\delta)}{\tilde{D}}\cdot s_c + \frac{(\alpha+b+\check{m}\delta)m}{\tilde{D}}\cdot t_c + \frac{\alpha a m}{\tilde{D}}. \tag{B6}$$

Differentiation of (B5) and (B6) immediately yields $R^\sigma_{s_c} \in]-1, 0[$, $R^\sigma_{t_c} > 0$, $R^\tau_{s_c} < 0$, $R^\tau_{t_c} > 0$ and $R^\sigma_{s_c s_c} = R^\sigma_{s_c t_c} = R^\sigma_{t_c t_c} = R^\tau_{s_c s_c} = R^\tau_{s_c t_c} = R^\tau_{t_c t_c} = 0$. In addition, differentiation of $R^\sigma_{s_c}$ with respect to m yields after rearrangement of terms

$$R^\sigma_{s_c m} = \frac{\alpha\left\{(\alpha+bn)(n^2-n) + \delta\left[(n^3-n^2+m^2) + b[n^4-(n-m)(2n^2-(n-m))]\right]\right\}}{\tilde{D}^2}. \tag{B7}$$

$R^\sigma_{s_c m}$ is strictly positive.

Appendix C. The signs of $\frac{\mathrm{d}p}{\mathrm{d}t_c}$ and $\frac{\mathrm{d}(p+t_c)}{\mathrm{d}t_c}$ under the conditions of equation (23)

From (8) and the equations (B5) and (B6) in Appendix B follows

$$\begin{aligned}
\frac{\mathrm{d}p}{\mathrm{d}t_c} &= \frac{\mathrm{d}}{\mathrm{d}t_c}\left[\frac{\alpha[s_c^* + R^\sigma(s_c^*, t_c; m)]}{n} - \frac{mt_c + (n-m)R^\tau(s_c^*, t_c; m)}{n}\right] \\
&= \frac{\alpha R_{t_c}^\sigma}{n} - \frac{m}{n} - \frac{(n-m)R_{t_c}^\tau}{n} = \frac{\alpha\check{m}m(n-1)}{n\tilde{D}} - \frac{\check{m}m(\alpha+b+\check{m}\delta)}{n\tilde{D}} - \frac{m}{n} \\
&= \frac{m}{n\tilde{D}}\left[\alpha\check{m}(n-2) - \check{m}(b+\check{m}\delta) - \tilde{D}\right]. \qquad \text{(C1)}
\end{aligned}$$

Making use of $\tilde{D}$ from (B4) we obtain from (C1)

$$\begin{aligned}
\frac{\mathrm{d}p}{\mathrm{d}t_c} \gtreqless 0 \quad &\Longleftrightarrow \quad \alpha\check{m}(n-2) - \check{m}(b+\check{m}\delta) - \tilde{D} \gtreqless 0 \\
&\Longleftrightarrow \quad -\left[\alpha(\check{m}+m)(n-2) + bn^2 + \delta(n^2 + \check{m}^2 - \check{m})\right] \gtreqless 0. \qquad \text{(C2)}
\end{aligned}$$

From (C2) we conclude that $\frac{\mathrm{d}p}{\mathrm{d}t_c} < 0$. That is, the coalition countries' terms of trade deteriorate, if the tariff rate t_c declines. Under the conditions of equation (23) the coalition countries' consumption welfare decreases following a decline in t_c, if $\frac{\mathrm{d}(p+t_c)}{\mathrm{d}t_c} \geq 0$, because the declining producer price reduces the coalition countries' fuel production. That reduction would then also reduce the consumption of good X, because more fuel must be imported under less favorable terms of trade. The response of the producer fuel price to variations of t_c is

$$\begin{aligned}
\frac{\mathrm{d}(p+t_c)}{\mathrm{d}t_c} \gtreqless 0 \quad &\Longleftrightarrow \quad \frac{\alpha R_{t_c}^\sigma}{n} + \frac{\check{m}}{n} - \frac{(n-m)R_{t_c}^\tau}{n} \gtreqless 0 \\
&\Longleftrightarrow \quad \alpha m(n-2) - m(b+\check{m}\delta) + \tilde{D} \gtreqless 0 \\
&\Longleftrightarrow \quad \alpha m\check{m}(n-1) + bn(n-1) + \delta(n^2 - \check{m} - m^2) \gtreqless 0, \qquad \text{(C3)}
\end{aligned}$$

which yields $\frac{\mathrm{d}(p+t_c)}{\mathrm{d}t_c} > 0$.

Appendix D. Concavity of the welfare function for the example of Section 3 (with $m = 4$)

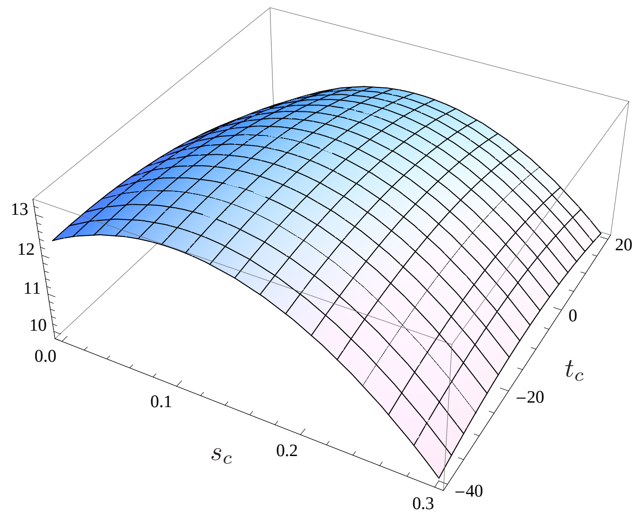

Figure 11: Concavity of the welfare function $m\tilde{W}^{ct}(s_c, t_c, mR^{\tau}(s_c, t_c; m), R^{\sigma}(s_c, t_c; m); m)$