Between a Rock and a Hard Place: A Trade-Theory Analysis of Leakage under Production- and Consumption-Based Policies

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Abstract

Without a comprehensive global climate agreement, carbon leakage remains a contentious issue. Trade policy – in particular the two equivalent concepts of border tax adjustment (BTA) and consumption-based emission accounting – is currently discussed as a potential means for increasing the effectiveness of unilateral climate policy. Based on a theoretical analysis of a general equilibrium trade model, the results of this paper cast doubt on the effectiveness of BTA: First, the optimal domestic carbon tariff depends on the carbon intensity differential between the foreign country's exporting and non-exporting sector, and not the foreign country's and the home country's exporting sector, as suggested by the BTA approach. Second, implementing a consumption-based policy does not generally prevent or even reduce leakage. Third, for the case of EU as well as US unilateral climate policy, the empirical data suggest that applying BTA on imports from China or most other countries would in effect increase leakage.

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1 Introduction

The Kyoto Protocol establishes upper limits for the greenhouse gas emissions of industrialized (Annex-B) signatories, but exempts developing countries from any binding commitment. Under the Copenhagen Accord, which was adopted at the 2011 Cancún climate summit, all countries are free to choose their own emission targets, including none. In this context of a fragmented policy regime, a frequently discussed issue is the possibility that in response to ambitious reduction targets adopted by some countries, energy intensive industries might migrate to countries with a less stringent or non-existent regulation of emissions (e.g., Van Asselt and Brewer, 2010). Hence, in absence of a global climate agreement, domestic emission reductions of early-movers could to a significant part be offset by increased emissions in other parts of the world, a phenomenon commonly referred to as *carbon leakage* (e.g. Felder and Rutherford, 1993).

Underpinning this concern, empirical studies have recently exposed the large imbalances in 'embedded' carbon associated with merchandise trade flows between industrialized and developing countries, suggesting that the former to some extent 'outsource' their emissions to the latter in order to meet their Kyoto commitments (Davis and Caldeira, 2010). Measures proposed to tackle this issue include approaches in which countries with emission caps are held accountable for their consumption instead of their production-related emissions (Peters and Hertwich, 2008b; Pan et al., 2008), or in which carbon prices are levied on imported goods by means of a border tax adjustment, or BTA (Ismer and Neuhoff, 2007).[1]

The debate on these instruments has mostly focused on two issues: technical feasibility and conformity with international trade law. On the first aspect, it has been pointed out that putting a price on carbon emitted in the production process of imported goods would face a serious obstacle due to the limited availability of information on the total carbon content of goods (Dröge, 2009). Second, international trade legislation (WTO) clearly

[1] Following Ismer and Neuhoff (2007), "a border tax adjustment consists of the imposition of a charge on imported products corresponding to a tax borne by like domestic products and the exemption from or remission of taxes on products when they are exported".

limits countries' ability to impose tariffs on imports. However, in certain circumstances it permits collecting taxes to protect the natural environment if they do not discriminate against foreign products (Perez, 2005), leading several authors to argue that BTA on carbon embedded in imported goods may be compatible with WTO regulations (Bhagwati and Mavroidis, 2007).

Even though a number of numerical CGE studies conclude that BTA could moderately reduce carbon leakage (cf. Section 2), the theoretical foundations behind this result have received surprisingly little attention. Against this backdrop, the present article re-examines the economic rationale behind the use of carbon-tariffs by employing a stylized 2x2 general equilibrium trade model, which generalizes the framework of Markusen (1975). We adopt the point of view of one region ('Home') implementing climate policy in face of the rest of the world ('Foreign'), where the latter region does not impose any policy measures. Three main results are derived: First, it is demonstrated that border tax adjustment and consumption-based accounting of emissions do not generally constitute optimal policy instruments for a country pursuing unilateral climate policies. The reason for this is that the optimal domestic carbon tariff depends on the carbon intensity differential between Foreign's exporting and non-exporting sectors, and not Foreign's and Home's exporting sector, as would be suggested by the BTA approach. Second, implementing a consumption-based policy does not generally prevent or even reduce leakage; instead, the effect is shown to be ambiguous and to depend on parameter values. Third, for the case of EU and US unilateral climate policy, the empirical data suggests that applying a BTA on imports from China would in effect increase leakage.

These findings cast considerable doubt on the practical feasibility of trade measures to effectively reduce carbon leakage. Consumption-based accounting of emissions - or equivalently BTA - is fraught with substantial uncertainty regarding economic effects and parameters and their alleged positive effects remain unproven. We conclude that it seems debatable if these measures rightly deserve the prominent place they occupy in the current debate and raise the question if their surprisingly wide-spread support in the political arena can perhaps rather be explained by protectionist motives than by environmental considerations.

This article proceeds as follows: Section 2 provides a survey of the relevant literature. Section 3 introduces our theoretical model. Section 4 examines the optimal design of unilateral climate policy. Section 5 examines production- and consumption-based policies and shows that the latter is equivalent to a border tax adjustment. Section 6 compares the policy measures examined before. Section 7 confronts our theoretical results with empirical data and discusses the results critically. Section 8 concludes.

2 Literature Review

The literature on unilateral climate policies has identified several channels through which carbon leakage can occur. These include (i) free-riding on one actor's provision of the global public good 'abatement' (e.g. Carraro and Siniscalco, 1993; Barrett, 1994), (ii) supply side interactions in which reduced demand for fossil fuels in countries that adopt a climate policy depresses their price and results in increased consumption elsewhere (Sinn, 2008), and (iii) changes in specialization patterns such that the production of emission intensive goods shifts to countries with a lower (or zero) carbon price (c.f. Siebert, 1979). Since the current debate on competitiveness - and the ensuing calls for 'leveling the carbon playing field' (Houser et al., 2008) - is mainly related to specialization leakage, which also constitutes the most relevant channel in terms of trade policy considerations, our analysis will focus on this particular channel of leakage.

Despite the fact that for most industries energy accounts for only a small fraction of total costs and that therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008), several numerical models have come up with rather high estimates of leakage rates of up to 45% (e.g. Felder and Rutherford, 1993; Babiker and Rutherford, 2005; Elliott et al., 2010).[2] Moreover, empirical studies analyzing the trade flows between industrialized and developing countries repeatedly find

[2] Naturally, leakage estimates depend on which countries join the policy regime and on the carbon tax level.

that the former are significant net importers of carbon emissions embedded in traded goods, especially with regard to China (Davis and Caldeira, 2010; Peters and Hertwich, 2008a; Wang and Watson, 2008; Shui and Harriss, 2006; Pan et al., 2008). Peters and Hertwich (2008a), for instance, estimate that China's net carbon exports amounted to about 18% of its total carbon emissions in 2001.

As a consequence, it has been concluded that either measures that target carbon emissions on a consumption instead of a production basis (Peters and Hertwich, 2008b), or policies in which carbon prices are levied on emissions arising from the production of imported goods in the form of border taxes (Ismer and Neuhoff, 2007; Monjon and Quirion, 2010) would be appropriate to address carbon leakage. However, several studies based on numerical models have found that border tax adjustments would have a rather limited potential to reduce carbon leakage (Babiker and Rutherford, 2005; Böhringer et al., 2010), leading several authors to conclude that border tax adjustments would strengthen sectoral competitiveness rather than decrease overall carbon leakage (Alexeeva-Talebi et al., 2008; Kuik and Hofkes, 2010).

The role of trade policy in the presence of international pollution has also been investigated from a theoretical point of view, albeit to lesser extent. Markusen's (1975) seminal analysis of unilateral environmental policy – on which our model is based – emphasizes that the only means to influence foreign producers' emissions by trade policy is through changes in the terms of trade. He also derives the result that in general two policy instruments (such as a production tax and a tariff) are needed to achieve an optimal outcome. This is confirmed by Hoel (1994) and Golombek et al. (1995), who show that with limited participation in an international climate agreement, the participants' optimal policy mix consists of taxing both the production and consumption of fossil fuels. In a similar vein, Hoel (1996) finds that a differentiation of carbon prices between sectors is not needed as long as one can use import and export tariffs on all traded goods.

One of the few theoretical studies addressing tariffs in proportion to the pollution content of imports is Copeland (1996), who demonstrates that such a tariff is an optimal way for dealing with transboundary pollution whenever the latter arises only from "border-zone production", i.e. from a sector that produces exclusively to meet demand in the importing country. For the case of climate change, of course, such a restriction cannot be applied. This is where the present contribution aims to add to the literature: by building on the theoretical literature cited above, but not restricting the analysis to optimal policies (be they first- or second-best), we study the theoretical foundations underlying the economic rationale of BTA and consumption-based accounting. In particular, we can provide – in a fairly general setting – the conditions under which these 'real world' policies reduce leakage or not.

3 The Model

In order to study the effects of unilateral climate policies in an open economy, we take the reduced-form general equilibrium trade model employed by Markusen (1975) as a starting point. This two-country, two sector model has the advantage of being general (consistent with both Heckscher-Ohlin and Ricardo-Viner framework) and easily tractable. However, while Markusen adopts the common assumption[3] that pollution arises only in the production of one of the two goods, our model is more general and allows each sector in each country to have a specific (but fixed) pollution intensity. As will be shown in the course of this analysis, the more restrictive – and seemingly innocent – assumption of only one polluting sector might lead to fallacious policy conclusions with regard to measures designed to counteract carbon leakage.

Specifically, let us assume a world of two regions, $r = \{h, f\}$, Home (h) and Foreign (f) producing two tradable goods, X and Y. Let Home – without loss of generality – offer both goods X and Y on its domestic market but only good X on the international market; conversely, let Foreign offer goods X and Y on its domestic market, too, but only good Y on the international market. Thus, X is traded from Home to Foreign, while Y is traded from Foreign to Home.

[3] This assumption is also adopted in, e.g., Copeland (1996) and Elliott et al. (2010).

Let X be the numéraire good (i.e. $p_X = 1$), $p = p_Y / p_X = p_Y$ the domestic price ratio in Home, and p^* the world market price ratio. For convenience, let us assume that Foreign does not implement any relevant policy so that economic agents in Foreign face the world market price p^*. Both countries' production is described by their production possibility frontier, i.e. the feasible set of combinations of output quantities Q of X and Y produced by using fixed factor supplies and technologies:

$$F^r(Q^{Xr}, Q^{Yr}) = 0 \tag{1}$$

Since Home and Foreign generally differ in their production possibility frontiers, each region has a comparative advantage in the production of one of the goods (here assumed to be good X for Home), making it rational to participate in international trade.[4] We can also reformulate Eq.(1) as a transformation function T^r describing the output of X as a concave, decreasing function of the output of Y:[5]

$$Q^{Xr} = T^r(Q^{Yr}), \quad T^r_{Q^{Yr}} < 0, \quad T^r_{Q^{Yr}Q^{Yr}} < 0 \tag{2}$$

Because output is implicitly determined by profit maximization of competitive producers, an increase in the price ratio p of good Y relative to good X shifts production towards Y, such that the output ratio Y / X rises.

As our model is static, we do not allow for international debt and require trade to be balanced. Let E^{Xh} denote Home's exports of X and M^{Yh} its imports of Y. Then[6]

$$E^{Xh} + p^* M^{Yh} = 0 \tag{3}$$

[4] Nevertheless, full specialization is excluded in our model since the marginal product of production factors will rise towards infinity when production levels approach zero.
[5] We denote derivatives with respect to a certain variable by subscripts throughout the analysis.
[6] This is equivalent to $p^* E^{Yf} + M^{Xf} = 0$ from Foreign's point of view. Our two-region setting naturally implies market clearance on all markets such that $E^{Yf} = M^{Yh}$, $E^{Xf} = M^{Xf}$.

The consumption side is characterized by a representative agent in each region drawing utility from the consumption of goods X and Y.[7] In formal terms, we assume homothetic preferences over consumption in form of a concave, increasing function U^r of C^{Xr} and C^{Yr}:

$$U^r(C^{Xr}, C^{Yr}), \quad U^r_{C^{Xr}} > 0, \quad U^r_{C^{Xr}C^{Xr}} < 0, \quad U^r_{C^{Yr}} > 0, \quad U^r_{C^{Yr}C^{Yr}} < 0 \tag{4}$$

From Home's point of view, consumption is related to exports and imports by:

$$C^{Xh} = Q^{Xh} - E^{Xh}, \; C^{Yh} = Q^{Yh} + M^{Yh} \tag{5}$$

Next, we introduce the global environmental externality in the form of climate change damages D^r caused by total emissions Z. Damages are assumed to reduce the utility drawn from consumption but leave productivity unaffected ('eyesore' pollution). To keep matters simple and transparent, let us assume that Home's welfare function W^h is linearly separable in U^h and D^h:

$$W^h = U^h(C^{Xh}, C^{Yh}) - D^h(Z), \quad D^h_Z > 0 \tag{6}$$

As a further simplification, let us assume that damages D^h are linear in global carbon emissions Z.[8] Since impacts of climate change in Foreign do not influence Home's utility, we only consider climate damages in Home. These are characterized by constant marginal damages ε:

$$D^h(Z) = \varepsilon Z, \quad \varepsilon > 0 \tag{7}$$

Global emissions are the sum of emissions in Home and Foreign, which we assume to be proportional to the output of X and Y in each region. To this end, we define sector and

[7] Imported and domestically produced goods are perfect substitutes from the consumer's point of view.
[8] The results can also be derived for the more general form, where ε is replaced by $\partial W / \partial Z$. However, for the insights to be highlighted in this paper the simpler form is fully sufficient and eases the notation.

country specific emission intensities γ^{Xr}, γ^{Yr} that denote the quantity of carbon emissions per (physical) unit of output:

$$Z = Z^h + Z^f = \gamma^{Xh}Q^{Xh} + \gamma^{Yh}Q^{Yh} + \gamma^{Xf}Q^{Xf} + \gamma^{Yf}Q^{Yf} \tag{8}$$

This assumption follows Markusen (1975) and implies that the production of one unit of a certain good in a certain region requires a certain fixed amount of fossil fuel inputs, and that there is no possibility to substitute among inputs to alter this ratio. Of course, long-run changes in production technologies, such as fuel switches and measures to increase energy efficiency, can be expected to influence these emission factors. However, the assumption of fixed emission factors seems plausible for a short-term analysis, and, more importantly, allows us to concentrate on the central general equilibrium aspects.

Finally, we assume that Home has market power on international markets. With a unique Foreign excess supply for any world market price p^*, Home's influence on p^* can be represented by a function G^h: [9]

$$\frac{dp^*}{dM^{Yh}} = p^*_{M^{Yh}} \equiv G^h > 0, \quad p^*_{E^{Xh}} < 0 \tag{9}$$

In other words, the price of Y rises due to an increased excess demand for Y through imports into Home. Similarly, the relative price of X falls due to an increased excess supply of X through exports from Home. Obviously, Home's market power influences Foreign's production and consumption through the change in the relative price p^*. It allows Home to behave strategically by influencing the terms of trade. Let us assume that Foreign on the contrary acts as a price taker who does not react strategically. With Home taking its impact on the world market price p^* into account, its imports become a choice variable, which – given the one-to-one correspondence of Foreign demand and price p^* – implicitly determines p^*.

[9] This is simply the equivalent of Markusen's (1975) assumption of $E_1 < 0$.

4 Optimal Unilateral Policies

From Home's perspective, optimal policies are those that maximize its welfare as given in Eq.(6), taking into account Eqs.(2) to (5) and (7) to (9). After a simple replacement of output and exports of good *X*, welfare maximization is tantamount to the optimal choice of domestic production and imports of good *Y*:

$$\begin{aligned}\max_{Q^{Yh}, M^{Yh}} W^h = \max_{Q^{Yh}, M^{Yh}} \{ & U^h[T^h(Q^{Yh}) - M^{Yh} p^*(M^{Yh}), Q^{Yh} + M^{Yh}] \\ & - \varepsilon[\gamma^{Xh} T^h(Q^{Yh}) + \gamma^{Yh} Q^{Yh} + \gamma^{Xf} T^f(Q^{Yf}(p^*(M^{Yh}))) + \gamma^{Yf} Q^{Yf}(p^*(M^{Yh}))]\}\end{aligned} \tag{10}$$

implying the two first-order conditions (i) $\frac{dW^h}{dQ^{Yh}} \overset{!}{=} 0$ and (ii) $\frac{dW^h}{dM^{Yh}} \overset{!}{=} 0$.

From condition (i) one obtains:

$$U^h_{C^{Xh}} T^h_{Q^{Yh}} + U^h_{C^{Yh}} = \varepsilon(\gamma^{Xh} T^h_{Q^{Yh}} + \gamma^{Yh}) \tag{11}$$

At Home's optimal point of production, the marginal benefit from producing an additional marginal unit of *Y* (with a corresponding reduction of *X*) balances the associated marginal change in damages. With profit-maximizing producers, the marginal rate of (technical) transformation of producing goods *X* and *Y* equals the producer price *p*. Therefore, we obtain from Eq.(1):

$$p = -T^h_{Q^{Yr}} \tag{12}$$

In the same manner, optimality of consumption is achieved when the marginal rate of substitution equals the consumer price, denoted by *q*:[10]

[10] Note that there is no need for a country index in the prices *p* or *q*: they always refer to Home, since by assumption Foreign does not employ any policy, and hence all prices in Foreign are given by *p**.

$$q = \frac{U^h_{C^{Yh}}}{U^h_{C^{Xh}}} \tag{13}$$

Inserting these expressions into Eq.(11) and dividing by $U^h_{C^{Xr}}$ yields:

$$p - q = q^Z (\gamma^{Yh} - p\gamma^{Xh}) \tag{14}$$

with $$q^Z = -\frac{\varepsilon}{U^h_{C^{Xh}}} \le 0 \tag{14b}$$

where q^Z denotes the price of the environmental externality in terms of *X*.

Condition (ii) can be written as:

$$U^h_{C^{Yh}} - U^h_{C^{Xh}}\left(G^h M^{Yh} + p^*\right) = \varepsilon Q^{Yf}_{p*} G^h\left(\gamma^{Yf} + \gamma^{Xf} T^f_{Q^{Yf}}\right) \tag{15}$$

It determines the optimal import quantity of good *Y* into Home, taking into account its impact on Foreign’s emissions via the change in world market prices. In the optimum, the marginal benefit from importing an additional unit of *Y* (and exporting a corresponding amount of *X*) exactly balances the associated marginal change in damages due to emissions resulting from Foreign’s changed point of production.

Writing the total differential of Eq.(12) – i.e. Foreign’s production possibility frontier – and solving for Q^{Yf}_{p*} allows to further specify the producers’ reaction to a change in p^*, the world market price of good *Y*:

$$Q^{Yf}_{p*} = -\frac{1}{T^f_{Q^{Yf}Q^{Yf}}} \equiv R^f > 0 \tag{16}$$

Finally, inserting Eqs.(12), (14) and (16) into Eq.(15), dividing by $U^h_{C^{Xr}}$, and re-arranging terms yields:

$$p^* - q = -G^h\, M^{Yh} + q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf}) \tag{17}$$

We can now determine the optimal production tax as well as the optimal import tariff on good *Y*, assuming that these policies only affect relative prices (i.e. are implemented through lump-sum transfers). The former is given by the difference between domestic producer and consumer prices, Eq.(14), and the latter by the difference between the world market price and the domestic consumer price, Eq.(17). This directly yields the expressions for the optimal tax τ on the production of *Y* and the optimal tariff θ, which are central results of our analysis:

$$\tau = q - p = -q^Z (\gamma^{Yh} - p\, \gamma^{Xh}) \tag{18}$$

$$\theta = q - p^* = G^h\, M^{Yh} \underbrace{- q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})}_{\theta^Z} \tag{19}$$

$$\theta^Z = -q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf}) \tag{19b}$$

The interpretation of Eq.(18) is straightforward: As the relative price *p* is the marginal rate of domestic transformation and substitution, respectively, any marginal change along Home's production possibility frontier that increases the production of good *Y* by one unit decreases the production of good *X* by *p* units. This, in turn, increases emissions by $(\gamma^{Yh} - p\, \gamma^{Xh})$ units and decreases utility by $q^Z(\gamma^{Yh} - p\, \gamma^{Xh})$. Hence, Eq.(18) simply states that the optimal production tax on good *Y* should internalize the emission externality arising from a marginal increase of domestic production of *Y*. Since $q^Z < 0$, we get $\tau > 0$ only if $\dfrac{\gamma^{Yh}}{p} > \gamma^{Xh}$, i.e. if production in Home's Y sector has a higher carbon intensity (in emissions per output value) than its X sector. [11]

Home's optimal tariff, as characterized by Eq.(19), consists of two parts: The first part, $G^h M^{Yh}$, does not depend on the environmental externality (as $M^{Yh} > 0$, this expression is non-negative). It represents the gains from influencing the terms of trade to depress the relative price of Home's imports, which is well known from the so-called 'optimal tariff' literature (c.f. Markusen et al., 1995, Ch.15). The second part, which we call the 'optimal carbon tariff' for the remainder of this paper, θ^Z (Eq. (19b)), captures the environmental externality associated with the import of good Y. According to Eq.(9), one additional import of Y raises the world market price by G^h. This affects Foreign's production pattern by increasing production of Y by R^f and decreasing production of X by $p^* R^f$ units. This leads to an increase in global emissions amounting to $G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})$ and lowers Home's welfare by $q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})$. The optimal carbon tariff simply internalizes this externality caused by a marginal increase of production of Y in Foreign by influencing world market prices (i.e. Foreign's terms of trade) accordingly, reaffirming Markusen's (1975) assertion that "[o]ne country cannot tax foreign producers, for example, but if the country has monopoly power in trade, it can generally influence foreign production by changing world commodity prices".

Proposition 1: *In the presence of a global environmental externality, Home's optimal carbon tariff θ^Z will be positive (negative) if – in terms of emissions per output value – Foreign's export sector is more (less) carbon intensive than its non-export sector.*

Proof: The proposition follows directly from the expression for θ^Z. ■

[11] The latter condition can perhaps be better understood when written as $\gamma^{Yh}/p_Y > \gamma^{Xh}/p_X$.

In a general equilibrium setting, imposing a positive tariff influences the terms of trade such that the relative price of Foreign's exports declines. This shifts Foreign's production from the export sector to the non-export sector and results in lower emissions in Foreign exactly if its export sector is more carbon intensive than its non-export sector. This finding is in line with Leamer (1980), who argues (i) that comparing a country's imports with its exports does not allow drawing conclusions regarding its comparative advantage and (ii) that trade theory suggests comparing exports with domestic consumption instead. In particular, comparing emissions embodied in Home's exports with those embodied in its imports does not give an indication of the sign of the optimal carbon tariff. This outcome tends to be overlooked in the current debate, as in a model with only one polluting good (as e.g. Markusen, 1975, or Elliott et al., 2010) comparing exports with imports is identical to comparing exports with domestic consumption.

Corollary 1: *When in both regions emissions are associated only with the production of the good that is imported by Home, then*

(i) *Home's optimal carbon tariff* θ^Z *will always be positive, and*

(ii) θ^Z *will be strictly proportional to the amount of embedded carbon in the imported good.*

To see this, set the emission intensities of sector X to zero, $\gamma^{Xh} = \gamma^{Xf} = 0$, and again evaluate Eqs.(18) and (19), leading to $\tau = -q^Z \gamma^{Yh}$ and $\theta^Z = -q^Z G^h R^f \gamma^{Yf}$, respectively. This reproduces Markusen's (1975) result, which – in a naïve interpretation – could be seen to suggest that the optimal carbon tariff depends *in general* only on the amount of carbon embodied in the imported good. However, in the case in which all goods cause emissions, this line of reasoning can be very misleading.

5 Existing and Proposed Policies: Production vs. Consumption-Based Approach

When thinking about actual policy implications, it appears not sufficient to examine exclusively the optimal carbon tariff. In the case of climate policy the use of market power for environmental purposes could be regarded as being highly controversial in political terms, which might explain why policy-makers have so far refrained from openly pursuing such policies. Instead, they resort to regulating domestic emissions, such as in the Kyoto Protocol or the European emissions trading scheme. However, as already discussed, this policy approach has been strongly criticized for its tendency to induce leakage, and policies based on consumed carbon have been proposed as a supposedly superior alternative. In the following section, we compare production- and consumption-based emission policies (also with respect to the optimal policy), and examine their impacts on leakage.

5.1. Production-Based Emission Policy

In this section, we derive the first-order conditions characterizing an equilibrium of the global economy when Home's only policy consists of adopting some production-based carbon constraint.[12] This represents the current state under the Kyoto Protocol, which obliges the large majority of industrialized countries to put a cap on the amount of carbon emissions *produced* on their territory. In our framework, this can be represented by Home implementing a suitable per-unit carbon tax on domestic emissions.

Formally, a per-unit carbon tax μ on emissions is equivalent to a tax levied on goods X and Y proportional to the emissions generated during their production. As a consequence, the standard first-order conditions equating producer prices (net of taxes) to the marginal rate of transformation and consumer prices to the marginal rate of substitution (c.f. Eqs.(12) and (13)) applying to profit-maximizing firms and utility-maximizing consumers in Home are given by:

$$\frac{q-\gamma^{Yh}\mu}{1-\gamma^{Xh}\mu} = -T^{h}_{Q^{Yh}} = p \qquad (20)$$

[12] We use the term 'some' to indicate that the level of the policy is not derived by optimization but can be arbitrary. Hence, we do not discuss second-best production-based policies, as done by Markusen (1975).

$$q = \frac{U^h_{C^{Yh}}}{U^h_{C^{Xh}}} \tag{21}$$

Consequently, the implied wedge between producer and consumer prices in Home becomes:

$$q - p = \mu(\gamma^{Yh} - p\gamma^{Xh}) \tag{22}$$

This expression is identical to the optimal production tax τ of Eq.(18) whenever the carbon tax μ correponds to Home's social costs of carbon, i.e. $\mu = -q^Z$. Since by assumption there are no other taxes or distortions, we have $q = p^*$, which is equivalent to a tariff $\theta = 0$. By contrast, in general the optimal tariff described in Eq.(19) is only zero if Home can be considered a small economy, i.e. if $G^h = 0$.

Corollary 2: *If it has market power on the world market, a production-based emission policy is not optimal for Home*

This also implies that in the case without market power the production-based emission policy is optimal for Home.

Eqs.(20) and (21), as well as the tax level μ under which Z^h is realized can also be derived by solving Home's welfare maximization problem under the constraint that its *domestic* emissions Z^h do not exceed a certain emission cap $\bar{Z}^h$. Given that firms and consumers in Home have by themselves no means to coordinate and employ their (potential) market power, Home can be modelled as taking the international price p^* as given:

$$\begin{aligned} \max_{Q^{Yh}, M^{Yh}} W^h &= \max_{Q^{Yh}, M^{Yh}} U^h[T^h(Q^{Yh}) - M^{Yh}p^*, Q^{Yh} + M^{Yh}] \\ &\quad s.t. \quad \gamma^{Xh}T^h(Q^{Yh}) + \gamma^{Yh}Q^{Yh} \le \bar{Z}^h \end{aligned} \tag{23}$$

which implies a relation $\mu(\bar{Z}^h)$ and, along with the market clearing conditions, also $p^*(\bar{Z}^h)$. The latter implies that even though Home does not take its impact on world market prices explicitly into account, it actually influences Foreign's emissions via p^* when choosing $\bar{Z}^h$. This, of course, is the potential cause of leakage, i.e. a rise in Foreign emissions in response to a reduction in Home's emissions. To understand whether or not a production-based carbon tax μ causes leakage, we need to analyze the general equilibrium implications of an increase of μ (equivalent to a decrease of $\bar{Z}^h$) on Foreign emissions. The latter are given by:

$$Z^f = \gamma^{Xf} T^f(Q^{Yf}) + \gamma^{Yf} Q^{Yf} \tag{24}$$

Recall Eq.(16) stating $Q^{Yf}_{p*} = R^f > 0$ for the impact of a change in p^* on Foreign's production as well as $-T^f_{Q^{Yf}} = p^*$ from Eq.(12). We thus obtain for the marginal impact of a change in p^* on Foreign's emissions:

$$Z^f_{p*} = \gamma^{Xf} T^f_{Q^{Yf}} Q^{Yf}_{p*} + \gamma^{Yf} Q^{Yf}_{p*} = \left(\gamma^{Yf} - p^* \gamma^{Xf}\right) R^f \tag{25}$$

Lemma 1: *An increase in the relative world market price p^* for Foreign's export good Y will lead to an increase (decrease) in Foreign's emissions if the emission intensity (in terms of emissions per output value) in Foreign's export sector Y is higher (lower) than in its non-export sector X, i.e. if* $\dfrac{\gamma^{Yf}}{p^*} > \gamma^{Xf}$.

Proof: The term R^f is always positive – producers increase the output of good Y if its relative price increases), so that Eq.(25) is positive whenever the term in parenthesis is positive. ■

It is straightforward to see that the increase in the relative price for *Y* will shift Foreign's production towards *Y* and will thus raise Foreign's emissions if the *Y*-sector is the emission intensive sector relative to Foreign's *X* sector.

The general equilibrium effect of an increase in Home's production-based carbon tax μ is captured by the following Lemma:

Lemma 2: *An increase in Home's carbon-based production tax* μ *leads to an increase (decrease) in the relative world market price* p^* *if Home's Y-sector is more (less) emission intensive than its X-sector.*

Proof: See Appendix.

Intuitively, if Home's *Y*-sector is more carbon intensive than its *X*-Sector, the production-based carbon tax shifts Home's production from *Y* to *X*. Instead of demanding the domestic good *Y*, consumers raise their demand for *Y*-imports from Foreign, which raises the relative world market price of *Y*.

Based on Lemma 1 and 2, we can state the conditions under which leakage occurs:

Proposition 2: *A unilateral production tax on emissions in Home leads to leakage if the relatively more emission intensive sectors (in terms of emissions per real output value) in Home and Foreign produce the same good (e.g. good Y).*

Proof: By Lemma 2, if Home increases or introduces a production-based carbon tax μ on the goods produced by Home, the international price of the good with the higher emission intensity increases. By Lemma 1, leakage occurs in case of a price increase of the good that is relatively more emissions intensive in Foreign. ■

5.2. Consumption-Based Emission Policy

In analogy to the formalization of a constraint on production related emissions in Eq.(23), we can derive the market outcome under a consumption-based policy from a welfare maximization problem with a constraint for domestically *consumed* emissions, taking prices as given. This means, emissions that are implicitly exported via exports of goods are subtracted from Home's emission budget, while emissions that are implicitly imported via imports of goods are added. Home's emission constraint, therefore reads:

$$\gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh}p^*\right] + \gamma^{Yh}Q^{Yh} + \gamma^{Yf}M^{Yh} \le \overline{Z}^h \tag{26}$$

Home's behavior can thus be expressed as an optimization problem in terms of the choice variables Q^{Yh} and M^{Yh}. Using ρ as the Lagrange-multiplier that denotes the shadow-price of emissions embodied in Home's consumption - which are constrained to $\overline{Z}^h$ - we obtain:

$$\begin{aligned} \max_{Q^{Yh},M^{Yh}} W^h &= \max_{Q^{Yh},M^{Yh}} U^h[T^h(Q^{Yh}) - M^{Yh}p^*),\, Q^{Yh} + M^{Yh}] \\ &s.t.\;\; \gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh}p^*\right] + \gamma^{Yh}Q^{Yh} + \gamma^{Yf}M^{Yh} \le \overline{Z}^h \end{aligned} \tag{27}$$

This formulation of the problem does not include explicit carbon-based tariffs or border taxes; demand for Foreign's goods is only constrained by a purely domestic regulation of emissions embodied in consumption.[13]

With $\sigma = \dfrac{\rho}{U^h_{C^{Xh}}}$ as the consumption-based carbon tax, the first-order conditions are then straightforward to compute and given by:

[13] This representation also shows how the regulation of consumed emissions becomes formally equivalent to the regulation of production-related emissions if the specific intensities (in terms of emissions per value) of Home's imported goods and its exporting sector are identical. In other words, the asymmetry between consumption- and production-based approaches is caused by the difference between different sectors in Home and Foreign, not by the difference between domestic and Foreign goods of the same sector.

Producer: $$p = \frac{q - \sigma \gamma_y^h}{1 - \sigma \gamma_x^h} \qquad (28)$$

Consumer: $$p^* = \frac{q - \sigma \gamma_y^f}{1 - \sigma \gamma_x^h} \qquad (29)$$

We can now examine the wedges that the consumption tax drives between producer and consumer prices and between consumer and world market prices, respectively:

$$q - p = \sigma\left(\gamma^{Yh} - p\,\gamma^{Xh}\right) \qquad (30)$$

$$q - p^* = \sigma\left(\gamma^{Yf} - p^*\,\gamma^{Xh}\right) \qquad (31)$$

Hence, the consumption-based policy can be implemented as a combination of a tax on the production of Y (Eq.(30)) and a tariff (Eq.(31)). If the consumption-based carbon tax σ equals the social cost of carbon, then - as in the previous section - the resulting tax on the production of good Y corresponds to the optimal production tax identified in Eq.(18). From the representative consumer's point of view, the consumption-based carbon tax σ puts a price on the externality caused by embodied emissions. This applies to the choice between domestic X and domestic Y goods (Eq.(30)), as well as to the choice between domestic X and imported Y goods (Eq.(31)). In particular, the tariff is equivalent to levying the carbon price on emissions embodied in imports ($\sigma\gamma^{Yf}$) and reimbursing it for domestically produced goods that are exported ($-\sigma p^*\gamma^{Xh}$). This practice is generally known as *border tax adjustment* (BTA).

Intuitively, BTA combined with a production based carbon tax results in a policy that targets the consumption instead of the production of emissions. However, note that the tariff implied by a consumption-based policy (Eq.(31)) deviates from the optimal carbon tariff (Eq.(19)) by (i) not taking into account the reaction of the world market price (G^h)

and of Foreign producers (R^f), as well as by (ii) applying the differential in carbon intensity between Home's imports and exports instead of the difference between Foreign's export sector and its non-export sector. Evidently, a tax on carbon intends to internalize the negative impacts brought about by a certain quantity of emissions. The production tax follows this logic. But in a general equilibrium setting the idea of 'putting a price on carbon' cannot simply be transferred to imports. Reducing imports of emissions embodied in traded goods by a certain quantity clearly does not – due to induced changes in Foreign's production and consumption patterns – avoid the same quantity of emissions being released into the atmosphere.

Corollary 3: *A consumption-based emission policy is in general not optimal for Home.*

This observation also raises the question whether the economic logic underlying WTO regulations (cf. Bagwell and Staiger, 2004) can be sensibly applied to carbon taxes: Obviously, BTA constitutes an optimal instrument to internalize externalities arising from local consumption (which are addressed e.g. by taxation of alcohol or tobacco). Yet, this argument does not hold for a *global* consumption externality, as in general Home's government has no more authority to regulate foreign consumers than foreign producers.

We can now use Eqs.(28) and (29) to state the following Lemma:

Lemma 3: *An increase in Home's consumption-based carbon tax σ will lead to:*

(i) *an increase in the world price p^* for Foreign's export good Y if both Home's X- and Y-sector are more emission intensive than Foreign's export sector Y,*

(ii) *a decrease in p^* if both Home's X- and Y-sector are less emission intensive than Foreign's export sector Y,*

(iii) *an ambiguous outcome if one of Home's sectors is more and the other less emissions intensive than Foreign's export sector Y, and*

(iv) *an increase (decrease) in p^* if the X-sector has the same emission intensity in both regions and the Y-sector as well (i.e. in the symmetric case*

$\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$) and the Y-sector, which is Foreign's export sector, has a lower (higher) emission intensity than the X-sector.

Proof: See Appendix.

With the help of Lemma 3, we can now specify the effects of a consumption-based policy on carbon leakage:

Proposition 3: *A policy targeting emissions embodied in Home's consumption has the following effect: if Home's X- and Y-sector are both less (more) emission intensive than Foreign's export sector Y, a consumption-based policy will lower (raise) the international price of Home's import good Y and leakage will occur if Foreign's export sector Y is less (more) emission intensive than its non-export sector X.*

Proof: Lemma 3 can be used to determine whether the price of the imported good increases or decreases, and Lemma 1 can then be applied to assess Foreign's change of emissions and thus the incidence of leakage. ■

If Home's carbon intensity is higher than Foreign's in both sectors, the consumption-based carbon tax shifts Home's demand from domestic production to imports. As a consequence, production in Foreign shifts from the non-export sector *X* to the export sector *Y*, increasing emissions if the carbon intensity in Foreign's *Y*-sector is higher than in its *X*-sector.

The symmetric case ($\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$) deserves to be treated separately:

Corollary 4: *If the X-sector has the same emission intensity in both regions and the Y-sector as well, and the Y sector is more (less) emission intensive than the X sector, a consumption-based policy in Home will lower (raise) the international price of Y and in either case lower emissions in Foreign, i.e. induce negative leakage..*

Proof: Applying Lemma 3 (iv) in combination with Lemma 1.

In this special case, consumption based policies affect production in the same direction in both countries due to the assumption of symmetry. Therefore, such policies shift production from the relatively carbon intensive to the less carbon intensive sector in both regions so that leakage is avoided. This result is in accordance with Markusen's (1975) result, who assumes one clean and one dirty sector (i.e. $\gamma^{Xr} = 0$). We generalize this result for the case of two sectors with different emission intensities. However, note that it does not hold in the more general case in which no restrictions regarding the emission factors are imposed.

6 Comparison and Discussion of the Policy Measures

As border-tax adjustment in combination with production-based accounting of emissions and consumption-based accounting constitute equivalent instruments, there is no need to discuss them separately. Having identified the effects of optimal policies as well as those of production- and consumption-based approaches, we can now compare the policy options that are currently debated. According to Eq.(19), Home's optimal tariff consists of two parts, wherein only the second part – the optimal carbon tariff of Eq.(19b) – is related to the environmental externality. We adopt the point of view that the policies under consideration should only be evaluated in terms of their effectiveness regarding the environmental externality, not in how far they can be used as a protectionist device to influence the terms of trade in Home's favor. Therefore, we compare production- and consumption-based policies only with the optimal carbon tariff of Eq.(19b) and not with the overall tariff that would maximize Home's welfare (Eq.(19)). Otherwise, one could, for instance, arrive at the conclusion that a policy that actually increases leakage can increase welfare not because of its environmental effect, but simply because it exploits market power to decrease the relative price of imports.

6.1. Production vs. Consumption-Based Policies under Full Information

Corollaries 2 and 3 have already established that in general neither production- nor consumption-based polices are optimal. Hence, the following question arises: if production-based and consumption-based emission accounting are the only instruments available to policy-makers, which one should be preferred? From the discussion in Section 5 it should be clear that none of these instruments is *a priori* more successful than the other in addressing leakage (as their effects depend on specific parameter values). If the carbon price put on emissions related to production or consumption, respectively, corresponds to Home's social cost of carbon (i.e. $\mu = -q^Z$ and $\sigma = -q^Z$), the wedge between consumer and producer prices is equivalent to the optimal tax levied on the production of Y (Eq.(18)).

In order to establish a ranking between production- and consumption-based policies, we have to distinguish between the following two cases: (i) if the tariff implied by a consumption-based emission policy of Eq.(31) and the optimal carbon tariff of Eq.(19b) have opposite signs, consumption-based accounting would in fact increase leakage compared to the (zero) carbon tariff implied by the production-based measure. Hence, the latter is unambiguously closer to the optimal carbon tariff than the former. (ii) By contrast, if the signs of the consumption-based emission policy of Eq.(19b) and the optimal carbon tariff of Eq.(31) are identical, the tariff implied by a consumption-based emission policy clearly induces less leakage than the production-based one. However, this tariff could be higher than the optimal carbon tariff, with the result that the adverse impacts of price distortions exceed the positive effects of reduced carbon leakage. It is in this case not possible to make general statements regarding the welfare effects of consumption- versus production-based measures without further specifying G^h and R^f.

This leads us to the following proposition:

Proposition 4: *Production-based policies targeting emissions at Home better approximate Home's optimal carbon tariff of Eq. (19b) than consumption-based polices* *if Foreign's exports are less (more) emission intensive than its non-exporting sector and Home's export and non-export sectors are both less (more) emission intensive than Foreign's export sector.*

Proof: Comparing the expression for the optimal carbon tariff (Eq.(19b)) reveals that if Foreign's exports are less (more) emission intensive than its non-exporting sector, the optimal carbon tariff would be negative (positive). However, with consumption-based policies, the implied tariff given by Eq.(31) would be positive (negative) if Foreign's exports are more emission intensive than its imports from Home. Under the conditions of the proposition, the tariff implied by a consumption-based policy has the opposite sign of the optimal carbon tariff and thus clearly approximates Home's optimal carbon tariff less accurately than a tariff of zero (as implied by a production-based policy). ■

According to Lemma 3, if both Home's export and non-export sector are less (more) emission intensive than Foreign's export sector, a consumption-based policy lowers (raises) the price p^* of Foreign's exports. In this case, a consumption-based policy leads to more leakage than a production-based approach if Foreign's exports of Y are less (more) emission intensive than its non-export sector X (as stated in Lemma 1).

6.2. Border Tax Adjustment Using the Best Available Technology Approach

In view of the substantial informational requirements to successfully implement a consumption-based approach – and to circumvent potential problems related to the WTO-principle of non-discrimination – some alternatives have been proposed. These include the best-available-technology approach as adopted by the proposed Waxman-Markey Bill of the United States, which calculates emissions embodied in imports based on the home country's emission factors, i.e. assuming that the exporting country employs modern and efficient technologies equivalent to industrialized countries' standard (Ismer and Neuhoff, 2007).

Again assuming that the emission tax equals Home's social cost of carbon (i.e. that the production tax implied by Eqs.(22) and (30), respectively, equal the optimal one of Eq.(18), i.e. $\mu = -q^Z$ and $\sigma = -q^Z$), the following holds with regard to the ranking of consumption- versus production-based policies under a best-available technology approach:

Proposition 5: *With respect to consumption-based policies that use a best-available-technology approach,*

(i) *production-based polices better approximate Home's optimal carbon tariff of Eq.(19b) than consumption-based policies if the relatively more emission intensive sector in Home and Foreign produce different goods,*

(ii) *production- and consumption-based approaches cannot be ranked with respect to proximity to Home's optimal carbon tariff of Eq.(19b) if the relatively more emission intensive sectors in Home and Foreign produce the same good.*

Proof: Using Eq.(31) and setting Foreign's emission coefficients identical to Home's, the wedge between consumer and world market price becomes:

$$q - p^* = \sigma\left(\gamma^{Yh} - p^* \gamma^{Xh}\right) \tag{32}$$

Comparing Eq.(32) with the optimal carbon tariff of Eq.(19b) reveals that they have opposite signs if the relatively more emission intensive sector in Home and in Foreign, respectively, produce different goods (e.g. the *X*-sector in Home but the *Y*-sector in Foreign). Production-based measures (implying a tariff of zero) would then obviously be closer to the optimal carbon tariff than the one implied by the consumption-based policy, which carries the opposite sign. On the other hand, if the relatively more emission intensive sector in Home and Foreign both produce the same good, the tariff implied by the consumption-based policies has the same sign as the optimal carbon tariff. As the former can then either exceed or fall short of the optimal level, ranking consumption- and production-based measures in terms of Home's welfare is in this case impossible without additional information. ■

7 Practical Implications and Relevance

7.1. Confronting the Model with Empirical Evidence

This section confronts the propositions derived in the previous sections with the ‘real world’ empirical context. In particular, we refer to the dataset created by Davis and Caldeira (2010)[14] containing the carbon contents of exports, imports and total production as well as the corresponding values of exported, imported and produced goods. Using this dataset, Table 1 in the Appendix reports our own calculation of carbon intensities for a set of selected countries and regions. We focus on an assessment of trade measures that the European Union or the United States could possibly impose towards developing countries that produce rising amounts of carbon emissions, in particular towards China. In Table 1, the first three columns show the carbon emissions embodied in exports, imports and total production. The fourth column shows the ratio of the carbon intensity of exports to the carbon intensity of total production. A value greater than one thus indicates a higher carbon intensity in exports than in total production, and since total production consists of exports and the non-export sector also a higher carbon intensity in the export than in the non-export sector. Similarly, the last column shows the ratio of the carbon intensities of imports versus exports.

With regard to Proposition 1, the data reveal that the carbon intensity of exports is lower than the carbon intensity of total production and thus of the non-export sector for most countries (77 out of 95 in the full data base), including China. Therefore, according to our theoretical framework, the optimal carbon tariff on imports from these countries would be negative in the majority of cases, and imposing a positive carbon tariff would increase carbon leakage.

[14] Their supplementary online material provides data for 95 countries. We aggregated the data of the 24 EU member countries contained in the dataset into one EU region. Data for ‘World’ was already included.

In terms of Proposition 2, one can expect that – even though the carbon intensity of energy production widely varies – the ranking of economic sectors by carbon intensity is to a large extent determined by technological factors and hence similar across countries.[15] Hübler (2009), for example, computes carbon intensities of 30 goods based on the GTAP 7 data and finds a very similar ranking of carbon intensities for China, an aggregate of other developing regions, and an aggregate of industrialized countries. Hence, our theoretical results imply that leakage is likely to occur under a production-based policy.

An exemplary comparison reveals that the carbon intensities of exports and total production (and thus necessarily of the non-export sector, too) in the EU and the US are both lower than the carbon intensity of China's exports. Moreover, as for most countries, the carbon intensity of China's exports is lower than that of China's total production. Therefore, according to Proposition 3, leakage is likely to occur under a consumption-based policy or equivalently BTA. Furthermore, according to Proposition 4 consumption-based policies are in this case expected to result in higher leakage with respect to China. Hence, if implemented by the EU or the US, the resulting wedge between world market prices and domestic consumer prices approximates the optimal carbon tariff (which would in fact be negative) less well than production-based policies. One could also imagine that the EU introduces carbon based policy measures towards the US. In this case, the data reveal a lower carbon intensity of EU exports and total production than of both US exports and total production. However, carbon intensities of exports and of total production are almost equal in the US. Therefore, the optimal carbon tariff would be about zero. As a consequence, no matter whether China or the US are targeted, a production-based policy appears as the preferable policy for the EU.

The symmetric case of Corollary 4 requires identical carbon intensities in each sector across different countries. Basically, one can expect to find similar energy intensities because of the use of similar technologies for producing certain goods in similar economies. But the energy mix and thus the emission intensity of energy supply vary

[15] For example, the production of cement or steel is energy intensive and thus carbon intensive in all countries, while the provision of financial services has in general a rather low energy- and carbon-intensity.

greatly across countries. Therefore, an exact match of carbon intensities across countries, which is a necessary condition for Corollary 4, is unlikely in reality. It is not visible in Table 1 either; a detailed examination would require sectoral data, though.

Finally, as the most emission intensive sectors are similar across countries, Proposition 5 suggests that it is not possible to establish a clear ranking between production-based policies and consumption-based policies that use a best-available-technology approach.

7.2. Model Limitations and Caveats

Our model makes several stylized assumptions: It only represents trade between two countries in two goods and abstracts from the sectoral composition of traded goods, current account surpluses or deficits, changes in production technologies and factor inputs, strategic interactions, and additional channels of leakage (such as free-rider and supply-side leakage). Complex numerical models – such as computable general equilibrium (CGE) models – implement some of these aspects. As a consequence, it is conceivable that in these models BTA can to some extent reduce leakage. In this section, we address the stylized assumptions in detail.

First, with trade measures based on carbon contents, a model with multiple countries is likely to predict that trade gets redirected and increasingly takes place between those countries that have implemented climate polices on the one hand (trade creation), and between those countries that do not have such policies on the other hand (trade diversion). Hence, in such a setting the effect of carbon-based border measures can be expected to be diminished. Second, when taking the multi-sectoral composition of traded goods into account, a carbon-based tariff can be expected to shift the composition of trade towards goods with lower carbon intensities. It is not clear if in this case a carbon tariff has a stronger or a weaker effect than in a two-sector model. Third, an analysis of unbalanced trade could only be conducted within a dynamic model, and the question remains in how far environmental and trade policy are appropriate instruments to tackle underlying macro-economic imbalances. Fourth, our model describes emissions in each region by fixed emission factors. It can be argued that carbon-based tariffs pose an incentive for Foreign to adopt cleaner production technologies or switch to less carbon-intensive fuels or intermediate inputs (e.g. Copeland 1996). Fifth, carbon-based tariffs could not only act as an incentive for Foreign to decarbonize, but also trigger retaliation in the form of countervailing tariffs. Accounting for these strategic interactions would require a game-theoretic framework, which we consider to be beyond the scope of this paper. Sixth, even though additional channels of leakage other than specialization are clearly important, it is far from clear how they are affected by trade policy and how they should be represented in a trade model.

However, these limitations of our theoretical model do not invalidate our basic message: the rationale behind environmental policies is to provide the right incentives for firms and consumers by pricing in externalities. As we have demonstrated, trade policies influence patterns of production and consumption through their effect on the terms of trade, i.e. on relative prices. These general equilibrium implications are often overlooked in the current debate, leading to an under-appreciation of the practical consequences of measures like consumption-based accounting of emissions and border tax adjustment. In that sense, the simplifications in our model discussed above actually point to further complex issues that should be considered (and understood) before trade policy is used to advance environmental objectives.

8 Summary and Conclusions

This paper employs a reduced form general equilibrium 2x2 trade model to assess the implications of production- and consumption-based policies for the regulation of carbon emissions, where the latter approach can be implemented by the means of border tax adjustment (BTA). After identifying the optimal tariff to address carbon leakage, it carries out a comparison with existing and proposed policies. Finally, it confronts the theoretical results with empirical data. Our findings indicate that important general equilibrium effects have been neglected in previous analyses, possibly paving the way for misleading conclusions regarding the effectiveness of proposed policies such as consumption-based accounting of emissions and border tax adjustment. The model further reaffirms that trade policies can be expected to have an impact on foreign producers only to the extent to which the imposing country is able to influence world market prices (i.e. possesses market power), thereby emphasizing the limited possibilities to influence other countries' domestic production decisions offered by trade measures.

Comparing production- and consumption-based approaches for putting a price on carbon has revealed that in general neither corresponds to the optimal policy. However, imposing the optimal carbon tariff derived in Section 4 might not be feasible under WTO stipulations and, moreover, requires very specific information, such as the elasticity of world market prices with respect to changes in the home country's imports and the price elasticity of the foreign country's production. Therefore, the only choice left to policy makers might be between production-based and consumption-based approaches to target emissions. We have compared these policies and identified conditions under which one is unambiguously superior to the other (from the perspective of the country putting the policy in place). Based on empirical data, our results suggest that if implemented by the EU or the US towards China, carbon leakage is likely to occur under both production-based and consumption-based carbon policies, but production-based measures are preferable over consumption-based ones, as the latter would lead to an increase in leakage vis-à-vis the former. Similarly, for the EU a production-based policy is also preferable to a carbon-based policy targeted at the US.

From a policy perspective, the findings presented cast considerable doubt on the practical feasibility of trade measures to effectively reduce carbon emissions in other countries. As we have demonstrated, consumption-based accounting of emissions or equivalently BTA are fraught with uncertainty regarding economic effects and parameters. Their implementation would require a large amount of information and considerable political capital, while their alleged positive effects remain unproven. Thus, it seems at least debatable if these measures rightly deserve the prominent place they occupy in the current debate. Their surprisingly wide-spread support in the political arena – despite their questionable effects – can perhaps be explained by pointing to the incentive to use such environmental policies as a means to realize gains from influencing the terms of trade in the home country's favour, a practice that has been criticized as 'green protectionism' (Evenett and Whalley, 2009).

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Appendix: Table 1

Carbon intensity of Country or region	Exports [kg / $]	Imports [kg / $]	Production [kg / $]	**Exports /** production	Imports / exports
Singapore	0.14	0.36	0.48	0.28	2.66
Iran	0.93	1.24	2.66	0.35	1.33
Paraguay	0.20	0.85	0.49	0.42	4.16
Vietnam	0.96	0.86	2.28	0.42	0.90
Malaysia	0.66	0.32	1.51	0.44	0.48
Ecuador	0.47	0.90	0.99	0.48	1.91
Thailand	0.96	0.49	1.65	0.58	0.52
Morocco	0.48	0.67	0.80	0.60	1.39
Nigeria	0.86	0.83	1.42	0.61	0.97
Mauritius	0.33	0.82	0.54	0.61	2.48
Switzerland	0.07	0.42	0.11	0.61	6.09
Hong Kong	0.15	0.78	0.24	0.61	5.30
Costa Rica	0.23	0.47	0.36	0.63	2.07
Taiwan	0.55	0.38	0.85	0.65	0.69
Korea	0.48	0.62	0.73	0.65	1.30
Sweden	0.10	0.46	0.16	0.66	4.45
Pakistan	0.91	1.16	1.37	0.66	1.28
China	**2.13**	**0.49**	**3.05**	**0.70**	**0.23**
Mexico	0.43	0.57	0.60	0.72	1.32
Indonesia	0.91	0.75	1.26	0.72	0.83
Tunisia	0.58	0.53	0.80	0.73	0.92
Bolivia	0.77	0.79	1.03	0.74	1.03
European Union	**0.25**	**0.49**	**0.32**	**0.78**	**1.98**
Peru	0.41	0.85	0.48	0.85	2.09
Turkey	0.65	0.79	0.77	0.85	1.21
Egypt	1.73	0.88	1.99	0.87	0.51
Russian Federation	2.43	0.85	2.63	0.92	0.35
World	0.61	0.61	0.66	0.93	1.00
India	2.06	0.88	2.12	0.97	0.43
United States	**0.49**	**0.77**	**0.50**	**0.99**	**1.56**
Canada	0.57	0.52	0.57	1.01	0.92
Japan	0.30	0.91	0.28	1.06	3.05
New Zealand	0.36	0.68	0.32	1.12	1.89
Argentina	1.20	0.58	1.04	1.16	0.49
Brazil	0.78	0.78	0.55	1.41	1.00
South Africa	2.80	0.60	1.94	1.44	0.22
Norway	0.32	0.55	0.20	1.60	1.74
Australia	0.93	0.78	0.53	1.74	0.84

Table 1: Carbon intensities of exports, imports and total production, and measured relative to each other for selected countries derived from data in Davis and Caldeira (2010). Full table available upon request.

Proof of Lemma 2:

The market clearing condition for the *Y* world market reads: $M^{Yh} + E^{Yf} = 0$, where both M^{Yh} and E^{Yf} depend upon the world market price p^*. Moreover, the budget balance condition Eq.(3) implies: $p^* M^{Yh} = E^{Xh}$. E^{Xh} depends upon p^* as well as μ, which translates into M^{Yh}. This implies for the derivative of the market clearing condition with respect to a change in Home's carbon tax μ (equivalent to a change of the cap $\overline{Z}^h$): $M^{Yh}(p^*, \mu) + E^{Yf}(p^*) = 0$ and thus

$$\frac{\partial M^{Yh}}{\partial \mu} + \frac{\partial M^{Yh}}{\partial p^*}\frac{dp^*}{d\mu} + \frac{dM^{Yf}}{dp^*}\frac{dp^*}{d\mu} = 0 \quad \Rightarrow \quad \frac{dp^*}{d\mu} = \frac{-\frac{\partial M^{Yh}}{\partial \mu}}{\left(\frac{\partial M^{Yh}}{\partial p^*} + \frac{dM^{Yf}}{dp^*}\right)} \tag{33}$$

Under standard conditions, the terms in the denominator are negative (the 'law of demand').[16] Hence, we only need to compute the sign of the numerator. Using the fact that preferences over consumption are homothetic, Home's imports, $M^{Yh} = C^{Yh} - Q^{Yh}$, can be rewritten by inserting the standard expressions for the consumption of *Y* derived from utility maximizing given an income budget

$$M^{Yh} = \frac{\overline{\eta}}{q} I^h - Q^{Yh} \tag{34}$$

where $\eta(q)$ denotes the share of Home's real income, I^h, spent on good *X*, and $\overline{\eta}(q) = 1 - \eta(q)$ denotes the share of Home's real income spent on good *Y*. Consumption of *Y* decreases in the relative consumer price of *Y*, denoted by *q*. Since for the moment there are no consumer taxes in place, it is $q = p^*$. Expressing total income as $Q^{Xh} + p^* Q^{Yh}$ leads to:[17]

[16] Note that in the present setting both Home and Foreign behave as price-takers

[17] Since both goods, *X* and *Y*, are traded internationally, total income is expressed by applying the international price p^*.

$$M^{Yh} = \frac{\overline{\eta}}{p^*} Q^{Xh} - \eta\, Q^{Yh} = \frac{\overline{\eta}}{p^*} T^h (Q^{Yh}) - \eta\, Q^{Yh} \tag{35}$$

Since in Eq.(35) only Q^{Yh} depends explicitly on the production tax, μ, we find

$$\frac{\partial M^{Yh}}{\partial \mu} = \left(\frac{\overline{\eta}}{p^*} T^h_{Q^{Yh}} - \eta \right) \frac{\partial Q^{Yh}}{\partial \mu} = -\left(\overline{\eta}\, \frac{p}{p^*} + \eta \right) \frac{\partial Q^{Yh}}{\partial \mu} \tag{36}$$

Differentiating the first and the third part of the producers' efficiency condition in Eq.(20) with respect to Q^{Yh} and solving for $\frac{\partial Q^{Yh}}{\partial \mu}$ yields

$$\frac{\partial Q^{Yh}}{\partial \mu} = \frac{\gamma^{Yh} - q\gamma^{Xh}}{\left(1 - \gamma^{Xh}\, \mu\right)^2 \dfrac{\partial^2 T^h}{\partial \left[Q^{Yh}\right]^2}} \tag{37}$$

Confronting the last equation with Eq.(16) shows that it will be negative when $\gamma^{Yh} > q\, \gamma^{Xh}$. Therefore, Eq.(36) will be positive if and only if $\gamma^{Yh} > p^*\, \gamma^{Xh}$, where $p^* = q$. In this case, Eq.(33) will be positive as well. ■

Proof of Lemma 3:

To determine the effect of σ on p^*, we start by differentiating the market clearing condition, obtaining (cf. Eq.(33)):

$$\frac{dp^*}{d\sigma} = -\frac{\dfrac{\partial M^{Yh}}{\partial \sigma}}{\dfrac{\partial M^{Yh}}{\partial p^*} + \dfrac{\partial M^{Yf}}{\partial p^*}} \tag{38}$$

Again, both terms in the denominator are negative. To determine the sign of the numerator, we start by further specifying Home's consumption. With homothetic preferences, we have:

$$\frac{C^{Xh}}{C^{Yh}} = \frac{\eta(q)\, q}{\overline{\eta}(q)} \tag{39}$$

where $\overline{\eta} \equiv 1 - \eta$ denotes the share of income spent on good Y, as a function of the domestic consumer price q. Since in equilibrium consumption must exhaust the total real income I^h of home, i.e. $C^{Xh} + p^* C^{Yh} = I^h = Q^{Xh} + p^* Q^{Yh}$, we obtain:

$$C^{Yh} = \frac{\overline{\eta}\, I^h}{\eta\, q + \overline{\eta} p^*} \tag{40}$$

Using $M^{Yh} = C^{Yh} - Q^{Yh}$, one can simplify M^{Yh} to

$$M^{Yh} = \frac{\overline{\eta}\, Q^{Xh} - \eta\, q\, Q^{Yh}}{\eta\, q + \overline{\eta} p^*} \tag{41}$$

where the RHS can be expressed completely in terms of p^* and σ, since q and p are dependent via Eqs.(30) and (31). Calculating the derivative $\frac{\partial}{\partial \sigma}$ and collecting terms leads to:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q + \overline{\eta} p^*\right)\left(\eta\, q + \overline{\eta} p\right) + \frac{\partial q}{\partial \sigma}\left(\eta \overline{\eta} + q\frac{\partial \eta}{\partial q}\right) I^h\right]}{\left(\eta\, q + \overline{\eta} p^*\right)^2} \tag{42}$$

The derivative of η with respect to q is connected to the elasticity of substitution Σ of U^h by $\frac{\partial \eta}{\partial q} = \frac{(\Sigma - 1)\eta\,\overline{\eta}}{q}$, leading to the final expression:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q + \overline{\eta} p^*\right)\left(\eta\, q + \overline{\eta} p\right) + \frac{\partial q}{\partial \sigma}\eta \overline{\eta}\, \Sigma\, I^h\right]}{\left(\eta\, q + \overline{\eta} p^*\right)^2} \tag{43}$$

While the denominator is always positive, both terms of the numerator can be either positive or negative, depending on the sign of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$. Since $\Sigma > 0$, and $\frac{\partial Q^{Yh}}{\partial p}$ is positive as given by Eq.(16), we have the following three cases: (i) Eq.(43) and hence Eq.(38) for $\frac{dp^*}{d\sigma}$ are positive, i.e. p^* increases when σ increases, if $\frac{\partial p}{\partial \sigma} < 0$ and $\frac{\partial q}{\partial \sigma} < 0$ (or if one term is negative and the other term is zero); (ii) Eq.(43) is negative and hence p^* decreases if $\frac{\partial p}{\partial \sigma} > 0$ and $\frac{\partial q}{\partial \sigma} > 0$ (or if one term is positive and the other term is zero); (iii) the impact of σ on p^* is ambiguous if $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$ have different signs. To determine the signs of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$, we obtain from Eq.(31):

$$\frac{\partial q}{\partial \sigma} = \gamma^{Yf} - p^* \gamma^{Xh} \tag{44}$$

while combining Eqs.(30) and (31) yields for p and $\frac{\partial p}{\partial \sigma}$:

$$p = p^* + \sigma \frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1 - \sigma\, \gamma^{Xh}\right)} \quad \Rightarrow \quad \frac{\partial p}{\partial \sigma} = \frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1 - \sigma\, \gamma^{Xh}\right)^2} \tag{45}$$

Therefore, case (i) will hold if both of Home's sectors are more emission intensive than Foreign's export sector *Y*, case (ii) if both of Home's sectors are less emission intensive than Foreign's export sector *Y*, and case (iii) otherwise. In the symmetric case (iv), i.e. when $\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$, $\frac{\partial p}{\partial \sigma}$ will become zero and Eq.(43) will simplify so that the sign of $\frac{dp^*}{d\sigma}$ only depends on Eq.(44) for $\frac{\partial q}{\partial \sigma}$. Accordingly, $\frac{dp^*}{d\sigma}$ will be positive if the *Y*-sector is less emission intensive than the *X*-sector and negative if it is more emission intensive. ■