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WHO CARES ABOUT CARBON LEAKAGE?

THE ECONOMICS OF BORDER TAX ADJUSTMENTS UNDER INCOMPLETE CLIMATE TREATIES[*]

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Abstract

Optimal choices of border tax adjustments (BTA) – tariffs or subsidies on imports and exports – are derived for a coalition of countries working cooperatively to abate greenhouse gas emissions, under an exogenous emissions reduction target. Under a domestic target, the optimal BTA is determined by a terms of trade effect only; therefore there is no justification for a carbon based BTA. It follows that most policy modelling papers have used the wrong baseline (constant domestic target) to test the effectiveness of carbon based BTA's. Under a global target, the optimal BTA consists of the standard two components from earlier literature: the terms of trade component and an induced foreign emissions component. The common focus on carbon leakage as a major policy concern seems to be misplaced, since leakage represents the optimal rearrangement of production patterns, from the perspective of the coalition, in order to meet the target (domestic or global) in the least-cost manner.

Key words: *international environmental agreements, border tax adjustments, climate change, carbon leakage.*

JEL Classification: Q5.

Résumé

Les choix optimaux des ajustements fiscaux à la frontière (BTA) – soit les tarifs ou les subventions sur les importations et les exportations - sont présentés pour une coalition de pays qui travaillent de concert pour réduire les émissions de gaz à effet de serre, dans le contexte d'un cible exogène de réduction des émissions. Pour une cible domestique, le BTA optimal est déterminé uniquement par un effet des termes de commerce; donc il n'y a pas de justification dans ce cas pour un BTA basée sur les émissions de carbone dans la production du bien donné. Il s'ensuit que la plupart des exercices de modélisation ont utilisé la mauvaise base (cible domestique) pour tester l'efficacité de la base de carbone BTA. Par contre, pour une cible mondiale, le BTA optimal se compose de deux composants standards de la littérature antérieure: un composant pour les termes de commerce et un autre composant pour refléter les émissions de carbone dans la production du bien. L'accent mis souvent sur le phénomène des fuites de carbone semble être déplacées car les fuites représentent le réarrangement optimal des modes de production, du point de vue de la coalition, afin d'atteindre la cible (domestique ou mondiale) de la manière la moins coûteuse.

Mots clés : *les accords internationaux environnementaux, les ajustements fiscaux à la frontière, le changement climatique, les fuites du carbone.*

Classification JEL : Q5.

I. Introduction

Climate change presents a classic case of a global commons problem. Since there is no supra-national authority which can impose a global climate policy on individual nations, any progress in this area will be the result of voluntary cooperation, either in the form of explicit international treaties or less formal arrangements. A full, cooperative solution (complete treaty) may be better for most countries than a non-cooperative solution. However, for many countries an even better outcome may be to free ride – i.e. to pursue national self interest while enjoying the benefits of others acting cooperatively (for example, see Barrett 1994).

Indeed, the poor record of adherence to the Kyoto Protocol and the lack of success of international negotiations to draft a successor treaty suggest that any further progress on this issue will likely be achieved by incomplete coalitions of countries acting cooperatively or by individual countries acting unilaterally. Such partial approaches raise concerns about the effects on the competitiveness of industries in the countries involved. Specifically, the concern is that climate policies will increase costs for domestic producers and therefore put them at a disadvantage vis-à-vis foreign competitors which do not face such costs. As a result, foreign production of emissions-intensive goods will increase while domestic production decreases.

Obviously, domestic producers are concerned about the effect of lost sales on their profits. However, beyond profits, the relocation of production of emissions-intensive goods also leads to an increase in foreign emissions of greenhouse gases, which offsets reductions accomplished in the domestic market. This phenomenon is referred to as carbon leakage and is viewed as a symptom of an ineffective emissions control policy.

One response to the competitiveness / leakage problem, which has received considerable attention among policy modellers, is to implement carbon-based border tax adjustments (BTA’s) for the protection of emission-intensive industries in the home country. The carbon-based BTA – also referred to as a border carbon adjustment (BCA) or embodied carbon tariff (ECT) – is defined as the product of the domestic carbon price and the amount of pollution emitted in the production and transport of an imported (or exported) good. Among policy makers, BTA’s are viewed as tools to level the playing field between domestic producers, who face an emissions control policy, and foreign producers, who do not.

Stated differently, one may argue that the lack of emissions control policies in non-cooperating countries represents an unfair subsidy, as foreign producers receive the services of environmental sinks without paying for them. It follows that a countervailing duty is justified to offset this subsidy (Stiglitz 2006). For these reasons, recent policy proposals in the US and Europe have included provisions for carbon-based BTA's (see Winchester et al. 2011 and Fischer and Fox 2011 for details).

The use of BTA's to deal with policy differences among countries in the environmental sphere has received attention from both theoretical economists and policy modelers. On the theoretical side, Baumol and Oates (1975) show that, in the absence of international cooperation to control transboundary pollution, the optimal arrangement for an individual country (or a coalition of countries) that wishes to implement domestic pollution controls is to supplement these controls with tariffs on the import of goods from countries which do not control their emissions of the pollutant. Subsequent literature has grounded this insight in a more rigorous theoretical framework and included the use of export border adjustments on domestic industries, among other extensions (Markusen 1975, Hoel 1994, Ludema and Wooton 1994, Hoel 1996, Copeland 1996).[1]

The primary insight of this theoretical literature is that the optimal BTA for each good consists of two components.[2] The first component reflects the influence of the domestic country on the international price of the good in question. This component reproduces the standard optimal tariff argument from trade theory, which flows from the effect of changes in the country's imports and exports on its terms of trade (Van de Graaff 1949). The second component reflects the induced emissions in foreign (non-cooperating) countries related to the imported (exported) goods. These two components are only relevant for countries with influence over international prices – i.e. the large country assumption. For small countries with no influence over international prices, the optimal BTA (both components) is zero.

More recently, the policy modelling literature has taken up the issue of BTA's in climate policy, testing the impact of this tool on country welfare, competitiveness and carbon leakage. A number of conclusions emerge from this literature. First, carbon-based BTA's do achieve some reduction in leakage and / or provide some measure of protection for domestic industry, but most

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[1] The use of border adjustments also has a precedent in the field of commodity taxation – in particular the use of export rebates and import taxes to convert domestic commodity taxes from a source basis to a destination basis (Lockwood and Whalley 2010). However, the case of environmental policy is distinct, as environmental policies typically have a differentiated impact upon final goods prices, owing to the differentiated carbon embodiment among goods.

[2] Throughout the paper, optimality is understood in the sense of the second best, where some countries refuse to participate in a global climate treaty.

researchers find these effects to be rather modest compared with the high expectations that policy makers hold a priori (Winchester et al. 2011, Dissou and Eyland 2011, Fischer and Fox 2011, Hubler 2011, Babiker and Rutherford 2005).[3] Second, there is some disagreement regarding the welfare effects on the countries imposing the BTA's. Most researchers find that BTA's provide modest improvement in welfare for the imposing countries, but some conclude the imposing countries are made worse off (e.g. Schenker and Bucher 2010, Dissou and Eyland 2011). Finally, some authors conclude that BTA's entail a high cost in terms of global welfare or welfare of non-member countries (Winchester et al. 2011, Hubler 2011, Bohringer et al. 2011).

Comparing these results with the theoretical literature reveals an apparent contradiction: while theory indicates a clear role for BTA's in domestic climate policy (on the surface at least), the modeling literature presents a very ambivalent picture of the effectiveness of BTA's. Part of the explanation for this contradiction lies in differences in assumptions between the two literatures, while another part is related to heterogeneity of instruments and assumptions within the modelling literature.

Beginning with the modelling literature, some papers focus on carbon import tariffs (e.g. Bohringer et al. 2011, Dissou and Eyland 2011, Hubler 2011, Schenker and Bucher 2010, Winchester et al. 2011); some also include export subsidies or rebates on domestic carbon taxes as a separate scenario (e.g. Babiker and Rutherford 2005), while very few model both simultaneously (e.g. Bohringer et al. 2010, Fischer and Fox 2011). Some modeling papers calculate the BTA's based on the home country's emissions intensity (e.g. Dissou and Eyland 2011, Schenker and Bucher 2010), while others use the foreign country's emissions intensity (e.g. Babiker and Rutherford 2005, Bohringer et al. 2010, Bohringer et al. 2011, Fischer and Fox 2011, Hubler 2011). Winchester et al. (2011) is split on this matter, with the calculation of direct emissions based on the foreign country's emissions intensity and the calculation of indirect emissions (intermediate goods) based on the home country's emissions intensity.

Most papers in the modeling literature assume large countries, where imports and exports have an effect on world prices. In contrast, Dissou and Eyland (2011) assumes a small, open economy (no influence on world prices). Some modeling papers assume lump-sum recycling of carbon tax revenues or an equivalent arrangement of grandfathering of emission permits under a

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[3] Nonetheless, the effects for selected energy intensive sectors are more pronounced (Bohringer et al. 2010), and at least one recent exercise (Bohringer et al. 2011) was more optimistic regarding the reduction in carbon leakage that could be achieved through carbon-based BTA's.

cap-and-trade system (e.g. Babiker and Rutherford 2005, Bohringer et al. 2011, Hubler 2011, Schenker and Bucher 2010, Winchester et al. 2011), some papers recycle revenues through production subsidies (e.g. Dissou and Eyland 2011), while others compare both approaches to revenue recycling (e.g. Bohringer et al. 2010, Fischer and Fox 2011).

Turning to the comparison of the theoretical and modelling literatures, there are five major differences which will prove to be important. First, the theoretical literature is cast in the optimal policy paradigm, whereas most modeling exercises are cast in the cost minimization paradigm. In the former, the climate damage function is assumed to be known and the policy problem is to choose the socially optimal (welfare maximizing) levels of emissions control and BTA's. Equilibrium emission levels are endogenous in this framework. In contrast, under cost minimization, the damage function is not known and climate policy is determined by an exogenously given emissions target. Either tradable permits or a uniform carbon tax are implemented within the coalition to attain the emissions target in the least cost manner. BTA's are then added to the mix, and the effects on welfare, leakage and competitiveness are assessed by comparing scenarios with and without BTA's.

Reflecting this distinction, the two literatures differ in terms of their emphasis on either global emissions control or a domestic target. Under the optimal policy framework (i.e. the theoretical literature), damages depend upon global emissions, and therefore policy variables are chosen to control global emissions in an optimal fashion – i.e. maximizing the welfare of the coalition. In contrast, under cost minimization (i.e. the modeling literature), most coalition members are assumed to adopt a domestic emissions target (e.g. Babiker and Rutherford 2005, Hubler 2011, Winchester et al. 2011). Policy variables are chosen to achieve this target without regard for global emissions (although the effect on global emissions is assessed ex post through the discussion of leakage).[4]

Though not usually discussed, it is possible that a coalition of countries would wish to adopt a global emissions target in the cost-minimization framework, despite the existence of free riders. Such an arrangement could come about, for example, if a coalition of core countries agreed on the importance of controlling global climate, while resigning themselves to the existence of a fringe of free riders. The coalition would then choose the values of policy

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[4] In Dissou and Eyland (2011) and Fischer and Fox (2011), coalition members are assumed to implement a carbon tax, instead of a quantitative emissions target, and this tax is held constant across all scenarios. This arrangement results in emissions varying across scenarios, without regard for either a domestic or a global quantitative target.

variables (domestic emissions reductions or carbon tax, plus BTA’s) to achieve the global target, thereby taking into account foreign behaviour and leakage (e.g. Bohringer et al. 2010, 2011).

A third difference between the theoretical and modelling literatures concerns the role played by terms of trade effects in the calculation of BTA’s. While the theoretical literature identifies a clear role for terms of trade effects in the calculation of BTA’s, the modelling literature ignores this effect, focusing instead on the emissions-related component of BTA’s.

A fourth difference concerns the emissions base for calculating the BTA. The theoretical literature identifies induced foreign emissions resulting from imports and exports as the base for the BTA. In contrast, the modelling literature focuses exclusively on the embodied carbon of the imported or exported good, i.e. the carbon emitted during production and transport. In reality, there are likely to be important differences between these two concepts, since induced foreign emissions reflect demand and supply changes in response to prices whereas embodied carbon is a physical accounting concept related solely to production and transportation technologies. In fact, not only the magnitudes but in some cases the signs of these two measures may differ.

Combining the two previous issues yields a fifth difference between the theoretical and modelling literatures: the theoretical literature raises the prospect of an asymmetry between the treatment of imports and exports at the border. In particular, the two components of the optimal BTA formula – terms of trade effect plus induced emissions – are often expected to have the same sign for imports but opposite signs for exports. This asymmetry arises from the fact that the terms of trade component indicates a tax should be placed on a country’s exports (large country case) to exploit market power, while the induced emissions component indicates that a subsidy should be offered to exporters, to discourage foreign production and emissions. In contrast, both components are usually indicated to be a tax for imported goods. This asymmetrical treatment suggests that the optimal BTA for imports may be significantly larger in absolute value than for exports, and there may be unexpected sign behaviour, e.g. a *tax* for both imports and exports. In contrast, when it treats exports at all, the modelling literature always considers an export subsidy (e.g. carbon tax rebate).

These differences make it difficult to use the available theoretical literature to interpret the results obtained by the modeling literature. In order to improve the situation, the present paper presents a theoretical model of optimal coalition policy subject to an exogenous target. The model is that of Hoel (1996) minus the damage function and with a slight change in production notation. The optimal choices of carbon tax and BTA's are derived for both domestic and global emissions targets on the part of the coalition (i.e. members of an incomplete climate treaty).

The model confirms the importance of the issues noted above. Specifically, the optimal formula for the BTA's (i) is based upon induced foreign emissions rather than embodied carbon, (ii) it includes terms of trade effects, and (iii) it is asymmetric between import and export BTA's. Moreover, the distinction between domestic and global emission targets turns out to be crucial. Under a global target, the standard two part formula is obtained, with one part based on terms of trade effects and the other based on induced emissions. In contrast, under a domestic target, the optimal BTA consists of the terms of trade effect only, which means that there is no welfare-based justification for carbon based BTA's in this case. It follows that, by focusing on domestic targets, many modelling exercises should not be expected to show welfare improvements associated with the use of carbon-based BTA's, unless by coincidence carbon-based BTA's mimic the pattern of terms-or-trade effects. Moreover, the results call into question the wisdom of focusing on carbon leakage as a policy concern. Under a domestic target, leakage is simply one means among many for achieving the target in a cost-effective manner. Under a global target, leakage is of course less with a carbon-based BTA than without, but there is no reason to expect it would be cost-effective to drive leakage to zero.

At the same time, while the theoretical model provides greater clarity on what can be expected from simulations of carbon-based BTA's, there are significant obstacles to the implementation of the theoretically determined values of the BTA's, including the illegality under international trade law of basing border adjustments on terms-of-trade effects. Therefore, the main contribution of the theoretical model is to provide a benchmark for interpreting the results obtained in the policy literature.

The next section presents the general equilibrium model of trade and greenhouse gas emissions and derives the coalition's optimal choice of carbon tax and BTA's. This is followed by a section discussing the results and laying out some practical challenges in implementing BTA's. The final section concludes.

II. Exogenous emissions target in a general equilibrium framework

The present section derives the optimal coalition choices of domestic emissions policy, in the form of a carbon tax and border tax adjustments, in an analytical general equilibrium model of trade, subject to an exogenous emissions target. For simplicity, the world is divided into two regions, representing abating countries (the coalition) and non-abating countries. The coalition may consist of a single country, which adopts a go-it-alone policy, or multiple countries which agree to cooperate on a harmonized abatement policy (i.e. participants in an incomplete climate treaty).

The model (and notation) is that of Hoel (1996) without the damage function and with a slight change in production notation. There are n+1 goods. For the coalition, the consumption vector is $c = (c_0, c_1, \dots, c_n)$, where c_0 represents consumption of fossil fuels. The sub-vector $(c_0, c_1, \dots, c_\eta)$ denotes the set of tradable goods, where $\eta \leq n$, and $(c_{\eta+1}, \dots, c_n)$ denotes the set of non-tradables when $\eta < n$. Inputs supplied by households, such as labour, are represented as negative values in c. The coalition's welfare is represented by the utility function $U(c)$, which is increasing in all of its arguments.[5]

Net imports of the coalition are represented by the vector $m = (m_0, \dots, m_n)$, with $m_i = 0$ for $\eta < i \leq n$ by the definition of non-traded goods. Gross output of the coalition is denoted $y = (y_0, \dots, y_n)$ and gross input is denoted $z = (z_0, \dots, z_n)$, with all y_i and z_i non-negative. The usual approach of representing production plans in terms of net outputs cannot be employed here since domestic carbon emissions depend both on consumption and input of fossil fuels, i.e. $c_0 + z_0$. A particular good may be an output, an input, or both. Material balance requires that $y + m = c + z$.

The coalition's production is characterized by a transformation function $F(y, z)$, where $F_{y_i} > 0$ and $F_{z_i} < 0$ (subscript notation represents the partial derivative). The production possibility set is defined by $F(y, z) \leq 0$ and efficient production entails $F(y, z) = 0$. Substituting for y from the material balance condition gives the form which will be used below,[6]

$$F(c - m + z, z) = 0. \qquad (1)$$

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[5] A reduction in the supply of input *i* by households (e.g. labour) corresponds with an increase in the value $-c_i$.

[6] Note that Hoel (1996) uses $F(c - m, z) = 0$ for Equation (1) which neglects the occurrence of *z* in the material balance condition.

The model abstracts from transportation costs. For traded goods, foreign and domestic varieties of the same good are assumed to be perfectly substitutable, and therefore there is a uniform international price. In contrast, in the modelling literature, foreign and domestic varieties are assumed to be differentiated, and therefore foreign and domestic prices differ for the same good (the Armington assumption). Nonetheless, the same qualitative results regarding the optimal choice of BTA's can be obtained for this framework as for the perfect substitute case.

International prices of traded goods are functions of net imports and denoted $p(m) = \left(p_0(m),\ p_1(m), \dots, p_\eta(m)\right)$. The coalition's current account is represented as $p(m)m = \sum_{i \leq \eta} p_i(m)m_i$, and the pattern of trade is assumed to be such that the current account[7] is in balance; i.e.

$$p(m)m = 0. \qquad (2)$$

Total greenhouse gas emissions are given by the sum of domestic (i.e. coalition) consumption of fossil fuels, c_0, domestic inputs of fossil fuels in production, z_0, and foreign emissions, e. Foreign emissions are assumed to depend upon net imports through the intermediary of prices; i.e.

$$e = e(m) = f(p(m)) \,. \qquad (3)$$

In the simplest case, there are no cross product effects (i.e. $\partial p_i / \partial m_j = 0$ for $i \neq j$), and positively sloped supply functions (negatively sloped demand functions) entail $\partial p_j / \partial m_j > 0$. In this case, the sign of $\partial e / \partial m_j$ is the same as the sign of $\partial f / \partial p_j$. For energy intensive goods, it is expected that $\partial f / \partial p_j > 0$, as an increase in the price increases foreign production and therefore foreign emissions. In contrast, as argued by Hoel, for non-energy intensive goods, we may expect $\partial f / \partial p_j < 0$, as an increase in the production of the good draws inputs from the production of energy intensive goods and therefore reduces foreign emissions overall. When there are cross-product effects, the sign of $\partial e / \partial m_j$ is indeterminate *a priori*.

The exogenous emissions target is denoted $\bar{E}$. In the case of a global target, the emissions constraint is

$$c_0 + z_0 + e \leq \bar{E}, \qquad (4)$$

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[7] The generality of the model accommodates existing capital stocks, and therefore the net import vector, *m*, includes flows of capital services. In fact, the notation in (2) gives the negative of the current account.

i.e. the sum of the coalition's fossil fuel consumption, the coalition's fossil fuel input, and foreign emissions cannot exceed the target. In the case of a domestic target, the constraint reduces to

$$c_0 + z_0 \leq \bar{E}, \tag{4'}$$

i.e. the coalition does not seek to control foreign emissions.

The social optimum for the coalition is obtained by choosing consumption (c), net imports (m), and gross inputs (z) to maximize $U(c)$ subject to (1) – (4).[8] The optimal values of gross output, y, are then obtained from the material balance identity. All functions are assumed to be differentiable and to possess properties that guarantee existence of a solution to the maximization problem. For simplicity, we can restrict our attention to an interior solution. Results will be derived first for the global target, and then results for the domestic target will be obtained by dropping all terms related to e.

The Lagrangian function is

$$\mathcal{L}(c, m, z; \mu, \pi, \lambda) = U(c) - \mu F(c - m + z, z) - \pi \sum_{i \leq \eta} p_i(m) m_i + \lambda[\bar{E} - c_0 - z_0 - f(p(m))]$$

where μ, π, and λ are multipliers. The first order necessary conditions are obtained in the usual way, and, upon manipulation, they yield the following optimality conditions.[9]

$$\frac{U_0}{U_i} = \frac{F_{y_0}}{F_{y_i}} + \frac{\lambda}{U_i}, \qquad i = 1, \dots, n \tag{5}$$

$$\frac{-F_{z_0}}{F_{y_i}} = \frac{F_{y_0}}{F_{y_i}} + \frac{\lambda}{U_i}, \qquad i = 1, \dots, n \tag{6}$$

$$\frac{P_0 + T_0}{P_i + T_i} = \frac{(U_0 - \lambda) - \lambda e_0}{U_i - \lambda e_i}, \qquad i = 1, \dots, \eta \tag{7}$$

where $e_i \equiv \frac{\partial e}{\partial m_i} = \sum_{j=0}^{n} f_j \frac{\partial p_j}{\partial m_i}$ and

$$T_i \equiv \sum_{j \leq \eta} \frac{\partial P_j}{\partial m_i} m_j \, . \tag{8}$$

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[8] Maximization of utility subject to the exogenous emissions target is mathematically equivalent to minimizing abatement cost to meet the target, since abatement cost is defined as the difference between the maximum level of utility attainable in the absence of an emissions target and the level of utility attained subject to the target.

[9] We omit conditions relating to the optimal use of inputs in own production, e.g. the use of z_0 in the production of y_0. Such conditions arise in this problem due to the explicit accounting of gross inputs and gross outputs.

Condition (5) indicates that the marginal rate of substitution between fossil fuels and any other good is equal to the marginal rate of transformation plus the shadow value of the emissions constraint (expressed in units of good i) which in the present context represents the marginal cost of abatement. This result reflects the higher opportunity cost of fossil fuels in the constrained environment.

Condition (6) indicates that the level of fossil fuels in production of other goods should be chosen such that the marginal product (left-hand side) is equal to the marginal cost of fossil fuels (marginal rate of transformation) plus the marginal cost of abatement of emissions (expressed in units of good i).[10]

Condition (8) defines the terms-of-trade effect of increasing net imports of good i. For the simple case where (i) cross-product effects are zero ($\partial P_j/\partial m_i = 0$ for $i \neq j$), (ii) the foreign supply curve is upward sloping, and (iii) the foreign demand curve is downward sloping ($\partial P_i/\partial m_i > 0$ in both cases), it follows that $T_i > 0$ for imported goods and $T_i < 0$ for exported goods. These are the standard large-country results, whereby an increase in imports erodes terms of trade by increasing import prices and a decrease in exports (increase in net import of an exported good) improves terms of trade by allowing the country to exploit its market power.[11] Results are less clear, however, when cross-product effects are not zero.

Condition (7) shows the optimal relationship between relative prices of traded goods, adjusted for terms of trade effects, and the marginal rate of substitution, adjusted for the increased opportunity cost of consumption due to the emissions constraint. As Hoel (1996) observes, it is not the ratio of prices but of marginal import costs that matters; hence the adjustment for terms-of-trade effects. On the other side of the equation, the change in welfare arising from a marginal unit of consumption reflects both the direct marginal utility and the opportunity cost associated with resulting changes in domestic and foreign emissions.

Decentralization of the social optimum in a competitive economy involves a choice of carbon tax, θ, by the coalition, to be applied to purchases of fossil fuels, as well as border tax adjustments for each good, $\{t_i\}_0^n$. (By definition $t_i = 0$ for non-traded goods.) Thus the price vector in the domestic economy is $(p_0 + \theta + t_0,\ p_1 + t_1,\ \dots,\ p_n + t_n)$. If $t_i > 0$, it represents

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[10] Hoel's (1996) presentation of (6) omits the marginal rate of transformation on the right-hand side, which implies that fossil fuels are costless to produce. This error follows from the omission of z in the material balance condition. See footnote 6 supra.

[11] The signs on T_i are counter-intuitive because (2) is the negative of the current account.

an import tariff (case of $m_i > 0$) or an export subsidy (case of $m_i < 0$). If $t_i < 0$, it represents an import subsidy or an export tax.

The representative consumer's problem is to choose c to maximize $U(c)$ subject to the budget constraint $(p_0 + \theta + t_0)c_0 + \sum_{i=1}^{n}(p_i + t_i)c_i = 0$. As discussed above, household supply of inputs is represented by negative elements of c. Also, the assumption of perfect competition means that there are no firm profits to distribute to households (zero profit condition).

The Lagrangian function for the maximization is

$$\mathcal{L}(c;\omega) = U(c) - \omega\left[(p_0 + \theta + t_0)c_0 + \sum_{i=1}^{n}(p_i + t_i)c_i\right]$$

where ω represents the multiplier. Assuming an interior solution, the first-order necessary conditions for a maximum are:

$$U_0 - \omega(p_0 + \theta + t_0) = 0\ , \tag{9}$$

$$U_i - \omega(p_i + t_i) = 0\ ,\quad i = 1, \dots, n \tag{10}$$

plus the budget constraint. Combining the first two conditions yields the standard consumer result of marginal rate of substitution equal to the price ratio,

$$\frac{U_0}{U_i} = \frac{p_0+\theta+t_0}{p_i+t_i}\ , i = 1, \dots, n. \tag{11}$$

The representative producer's problem is to choose a production plan (y, z) to maximize profit subject to the production constraint $F(y, z) = 0$. Using the price notation above, profit is defined as $\sum_{i=0}^{n}(p_i + t_i)(y_i - z_i) - \theta z_0$. The Lagrangian function for the maximization is

$$\mathcal{L}(y, z; \Gamma) = \sum_{i=0}^{n}(p_i + t_i)(y_i - z_i) - \theta z_0 - \Gamma F(y, z)$$

where Γ represents the multiplier. Again assuming an interior solution, the first order necessary conditions are:

$$p_i + t_i - \Gamma F_{y_i} = 0\ ,\ i = 0, \dots, n \tag{12}$$

$$-(p_0 + t_0 + \theta) - \Gamma F_{z_0} = 0\ , \tag{13}$$

$$-(p_i + t_i) - \Gamma F_{z_i} = 0\ ,\ i = 1, \dots, n \tag{14}$$

plus the production constraint.

Since the structure of the model is largely the same as Hoel (1996), it happens that the same choices of the carbon tax and border tax adjustments will decentralize the optimal result (with the marginal abatement cost, λ, substituted where Hoel has marginal damages of emissions, E' in his notation). These choices are:

$$\theta = \lambda \frac{p_i + t_i}{U_i}, \qquad i \neq 0$$

$$t_i = T_i + \theta e_i, \qquad i \leq \eta \tag{15}$$

$$t_i = 0\,, \qquad i > \eta$$

These results entail a common carbon tax on all coalition uses of fossil fuels (i.e. on consumption c_0 and input z_0) and differentiated border tax adjustments on tradable goods.[12] In particular, the border tax adjustment consists of two components: the first is the terms of trade effect, T_i, and the second is the product of the domestic carbon tax (θ) and the change in foreign emissions induced by a marginal increase in the net import of the good (e_i).

In contrast, when the coalition has a domestic rather than global emissions target (condition $4'$), the term relating to foreign emissions drops out, yielding an optimal border tax adjustment for tradable goods equal only to the terms of trade effect, i.e.

$$t_i = T_i\,. \qquad \text{for } i \leq \eta \tag{16}$$

III. Discussion

Comparison of (15) and (16) yields several important lessons. First, the distinction between a domestic and a global emissions target is critical. Under a domestic target, there is no justification in the present framework for setting the BTA on the basis of carbon emissions, as shown by condition (16). Yet virtually all discussions of climate policy in the political arena are framed in terms of domestic targets, as in the Kyoto Protocol for example, and many policy modelling exercises do the same. For small countries, as expected, the optimal BTA is zero, since $T_i = e_i = 0$ in this case.

Second, flowing from this distinction between global and domestic targets, it emerges that carbon leakage from coalition members to non-members is not a compelling policy issue from the perspective of welfare economics. On the one hand, for a country that adopts a domestic

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[12] Note that the choice of i in the expression for θ is arbitrary, by virtue of (11). To verify the decentralization, observe that (i.) combining producer's condition (12) with consumer's condition (11) and the carbon tax (15) yields optimality condition (5); (ii.) combining producer's conditions (12) and (13) with the expression for the carbon tax (15) yields optimality condition (6); and (iii.) combining the carbon tax and BTA expressions from (15) with consumer's condition (11) yields optimality condition (7).

target, leakage represents one of a set of adjustment measures (others include technological change, end-of-pipe abatement measures, and behavioural change) that enable it to achieve its target in a cost effective manner. Therefore, restraining leakage represents an arbitrary and costly restriction on the country's adjustment process. On the other hand, given a global target, and abstracting from other possible market distortions, leakage reflects the most efficient reorganization of global production among countries subject to (i) the global target and (ii) the policy variables available to the coalition. As long as the global target is achieved, there is neither an economic nor an environmental rationale for worrying about leakage (although there may be a political rationale). In this vein, Bohringer et al. (2010) demonstrate that leakage may still be significant under a global emissions target, even in the presence of BTA's.

The third lesson is that, from a welfare perspective, most modelling exercises to date have assessed the performance of BTA's with reference to the wrong baseline. Modelling papers typically compare welfare for the coalition under a domestic emissions target with and without a carbon based BTA. In other words, the domestic target without BTA is taken as the baseline. Yet the theoretical results indicate that there is no welfare basis for a carbon-based BTA under a domestic target (although such a BTA may mimic the optimal "terms of trade" tax). In contrast, the theory affirms that, for a global emissions target, it will be welfare improving for the coalition to adopt a combination of BTA (based in part on induced carbon emissions) and carbon price (tax or permit regime), compared with a carbon price alone. Therefore, the baseline for comparison in this case involves achieving the global target using only a domestic carbon price (emissions tax or permit regime).[13] Bohringer et al. (2010 and 2011) provide examples of this type of comparison.

The fourth lesson is that, under a global target, the carbon component of the optimal BTA reflects induced foreign emissions resulting from a change in the net import of a good rather than embodied carbon. Induced foreign emissions result from changes in international prices, and therefore they aggregate multiple effects, whereas embodied carbon is a physical accounting concept related uniquely to the good in question. Using the notation of the previous section, embodied carbon of a unit of good i is represented by the derivative $\frac{dz_0}{dy_i}$, whereas the induced

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[13] The question of feasibility arises; i.e. is it possible for the coalition to achieve a particular global emissions target using only a tax or permit regime focused on domestic emissions? At the very least, if ex ante global emissions are X and domestic emissions are x, then it is feasible to achieve a global target of $\bar{X} \in [X - x, X]$, although the domestic sacrifice becomes progressively more extreme as $\bar{X}$ approaches the lower bound.

foreign emissions associated with the import of an additional unit of good i is represented by $e_i = \frac{d\hat{c}_0}{dm_i} + \frac{d\hat{z}_0}{dm_i}$ where the hat notation indicates foreign variables (e.g. $\hat{c}_0$ represents foreign final consumption of fossil fuels).

These expressions can be elaborated further. For embodied carbon, differentiate the production constraint $F(y, z) = 0$ to obtain

$$\frac{dz_0}{dy_i} = \frac{F_{y_i}}{-F_{z_0}}. \tag{17}$$

For induced foreign emissions, it is necessary to provide more structure for the foreign economy in order to proceed further. This is easily accomplished by adapting the structure and notation presented above for the domestic economy to the case of the foreign economy. In particular, observe that $m_i \equiv -\widehat{m}_i$; i.e. domestic net imports are equal to foreign net exports. Thus induced foreign emissions can be represented in terms of foreign variables as

$$e_i = \frac{d\hat{c}_0}{dm_i} + \frac{d\hat{z}_0}{dm_i} = -\left(\frac{d\hat{c}_0}{d\widehat{m}_i} + \frac{d\hat{z}_0}{d\widehat{m}_i}\right)$$

The derivatives $\frac{d\hat{c}_0}{d\widehat{m}_i}$ and $\frac{d\hat{z}_0}{d\widehat{m}_i}$ in the expression above involve the working of the price system on the entire foreign economy. To demonstrate, we can adapt the first-order conditions for the consumer (conditions 9 and 10) and the producer (conditions 12 – 14) from the domestic economy. For the foreign consumer, this yields

$$\widehat{U}_i - \widehat{\omega} p_i(\widehat{m}) = 0 \,, \ i = 0, \dots, n$$

plus the foreign consumer's budget constraint $\sum_{i=0}^{n} p_i(\widehat{m})\hat{c}_i = 0$. For the foreign producer, the first-order conditions are

$$p_i(\widehat{m}) - \widehat{\Gamma}\widehat{F}_{y_i} = 0 \,, \ i = 0, \dots, n$$

$$-p_i(\widehat{m}) - \widehat{\Gamma}\widehat{F}_{z_i} = 0 \,, \ i = 0, \dots, n$$

plus the foreign production constraint $\widehat{F}(\hat{y}, \hat{z}) = 0$. The only difference from the domestic first-order conditions is that the foreign economy does not implement a carbon tax or border tax adjustments.

Now define H^U as the $(n+1) \times (n+1)$ Hessian matrix of $\widehat{U}(\hat{c})$ and H^F as the $2(n+1) \times 2(n+1)$ Hessian matrix of $\widehat{F}(\hat{y}, \hat{z})$; i.e.

$$H^U = \begin{bmatrix} \widehat{U}_{00} & \cdots & \widehat{U}_{0n} \\ \vdots & \ddots & \vdots \\ \widehat{U}_{n0} & \dots & \widehat{U}_{nn} \end{bmatrix}$$

and

$$H^F = \begin{bmatrix} \hat{F}_{y_0 y_0} & \cdots & \hat{F}_{y_0 z_n} \\ \vdots & \ddots & \vdots \\ \hat{F}_{z_n y_0} & \dots & \hat{F}_{z_n z_n} \end{bmatrix}.$$

Further, let J represent the $1 \times 2(n+1)$ Jacobian vector of $\hat{F}(\hat{y}, \hat{z})$ and $p = p(\widehat{m})$ represent the $1 \times (n+1)$ price vector ; i.e.

$$J = \begin{bmatrix} \hat{F}_{y_0} & \dots & \hat{F}_{y_n} & \hat{F}_{z_1} & \dots & \hat{F}_{z_n} \end{bmatrix}$$

and

$$p = \begin{bmatrix} p_0(\widehat{m}) & \dots & p_n(\widehat{m}) \end{bmatrix} .$$

Then define a $(n+2) \times (n+2)$ coefficient matrix

$$M^U = \begin{bmatrix} H^U & -p' \\ p & 0 \end{bmatrix}$$

and a $(2(n+1)+1) \times (2(n+1)+1)$ coefficient matrix

$$M^F = \begin{bmatrix} \hat{\Gamma} H^F & J' \\ J & 0 \end{bmatrix} .$$

Finally, define a $(n+2) \times 1$ vector of price effects

$$C^U = \widehat{\omega} \begin{bmatrix} \partial p_0 / \partial \widehat{m}_i \\ \vdots \\ \partial p_n / \partial \widehat{m}_i \\ -\frac{1}{\widehat{\omega}} \sum_{j=0}^{n} \frac{\partial p_j}{\partial \widehat{m}_i} \hat{c}_j \end{bmatrix}$$

and a $(2(n+1)+1) \times 1$ vector of price effects

$$C^F = \begin{bmatrix} \partial p_0 / \partial \widehat{m}_i \\ \vdots \\ \partial p_n / \partial \widehat{m}_i \\ -\partial p_0 / \partial \widehat{m}_i \\ \vdots \\ -\partial p_n / \partial \widehat{m}_i \\ 0 \end{bmatrix} .$$

It is then a simple matter of comparative statics involving the first-order conditions to show that (i) $\frac{d\hat{c}_0}{d\widehat{m}_i} = \frac{|M_1^U|}{|M^U|}$ where M_1^U is the M^U matrix with C^U substituted into the first column, and (ii) $\frac{d\hat{z}_0}{d\widehat{m}_i} = \frac{|M_{n+2}^F|}{|M^F|}$ where M_{n+2}^F is the M^F matrix with C^F substituted into the $(n+2)^{\text{nd}}$ column (Cramer’s rule).

Pulling these results together yields the following expression for induced foreign emissions associated with an additional unit of domestic imports:

$$e_i = -\left(\frac{|M_1^U|}{|M^U|} + \frac{|M_{n+2}^F|}{|M^F|}\right). \qquad (18)$$

The role of price effects in evident through the vectors C^U and C^F, whereas the expression for embodied carbon (17) relates only to the production technology.

The two concepts of embodied carbon and induced foreign emissions may differ substantially, both in magnitude and in sign. For example, an increase in imports of an emission intensive good increases the price of the good (assuming an upward sloping supply curve), partially crowding out foreign consumption. Therefore, the induced foreign emissions are less than the embodied carbon of the additional imports. As another example, consider an increase in imports of a non-emission intensive good. As Hoel (1996) observes, this change increases foreign production of the good, pulling inputs out of the emission intensive sector. Therefore, there is a reduction in foreign emissions overall. Not only is the magnitude of induced emissions different than the embodied carbon of the imports in this example, but the sign is different as well.

The fifth lesson that can be drawn from the optimal policy expressions is that the model generates the expected asymmetry in the treatment of imports and exports under a global target. To illustrate, consider an emissions intensive good in the simple case with no cross product effects ($\partial p_i/\partial m_j = 0$ for $i \neq j$) and standard slopes. As argued in the previous section, $e_i > 0$ in this case, and therefore the emissions component of (15) is positive for both imports and exports. In contrast, as observed above, $T_i > 0$ for imported goods and $T_i < 0$ for exported goods in this case, and therefore the terms of trade effect of (15) has a different sign depending upon whether the good is a net import or net export. The overall effect is that the magnitude of the optimal BTA is larger for the imported good than the exported good, since the two terms of (15) have the same sign for the imported good but different signs for the exported good.

This asymmetry explains the rather ambivalent results obtained for carbon based export subsidies (carbon tax rebates) in the modelling literature (Babiker and Rutherford 2005, Bohringer et al. 2010). In particular, the carbon based BTA used in these papers is likely to provide a worse approximation of the optimal BTA for exports than for imports. Therefore, when tested in isolation, the carbon based export subsidy yields a poorer outcome in terms of coalition welfare than the carbon based import tariff.

Notwithstanding these insights, there are serious practical limitations to the implementation of the theoretically correct BTA formula. First, a BTA based upon terms of trade considerations (the first component of the BTA formula) is illegal under WTO trade law. Second, while foreign emission intensity is the correct basis for the emission component of the BTA (second term), it is likely that only domestic emissions intensity would be accepted under the WTO as the basis for this component (Fischer and Fox 2011, Ismer and Neuhoff 2007). Foreign and domestic emissions intensity differ significantly for some goods. For example, based on a multi-region input-output model, Bohringer et al. (2011) estimate that China's emission intensity exceeds the OECD average by a factor of three or more across a wide variety of sectors, including electricity, non-metallic minerals, iron and steel, coal, non-ferrous metals, water transport, and chemicals, rubber and plastics. Therefore, in many cases, substituting domestic for foreign emissions intensity will take us far away from the theoretically correct value of the BTA.

A third practical limitation is that estimation of the induced emissions component (18) of the BTA formula would place such enormous demands on modellers in terms of information as to be effectively infeasible. Yet even if induced emissions could be estimated with tolerable accuracy – and this represents a fourth limitation – the general equilibrium effects which are bound up in this component would also be subject to the same objections on legal grounds as the terms of trade effects. In the end, the only type of BTA that it likely to be both empirically estimable and WTO compliant is one that is based upon domestic embodied carbon – i.e. based upon the emissions in the production and transport of the particular good in the home country or coalition.

This reality has numerous implications for the use of border adjustments in climate policy. First, although there is no theoretical basis for carbon based BTA's under domestic emissions targets, they will nonetheless prove to be useful to abating countries (welfare improving) to the extent that they mimic the optimal "terms-of-trade" tariff which is otherwise illegal. (Of course, this tariff is zero for small, open economies.) This effect has been captured by much of the existing modelling literature.

Second, given the noted asymmetry between the optimal import and export measures, the carbon based import tariff is more likely to be welfare improving than the carbon based export subsidy. This effect has also been captured in the literature (Babiker and Rutherford 2005, Bohringer et al. 2010).

Third, in the context of a global target, carbon based BTA's will likely prove useful to abating countries as a supplement to carbon-price-only policies. In the absence of BTA's, carbon prices would need to be quite high in the abating countries, assuming an ambitious target. Conventional considerations of the minimization of deadweight loss suggest that broadening the base of the emissions policy, through the addition of BTA's, may be welfare improving for the coalition. In this vein, by partially pricing foreign emissions (the emissions related to traded goods), it is expected that the use of BTA's under a global target would reduce the required value of the domestic carbon price. These expectations are borne out by Bohringer et al. (2010). However, it remains true that the carbon based BTA is only an approximation of the theoretically correct (welfare maximizing) value, and there is nothing to guarantee that the approximation is good. Schenker and Bucher's (2010) conclusion that the BTA is not a credible threat for the abating region demonstrates this point.

Fourth, perhaps the most promising framework for considering BTA's is as an enforcement mechanism for participation in a global climate treaty. In this context, the relation of the tariff to embodied carbon or to the optimal value given by (15) is less important than its effectiveness in changing the strategic calculations of countries which would otherwise not join a treaty. In the best outcome – complete participation – such a tariff would never actually be implemented, and therefore its WTO legality and its relation to some theoretically ideal value would be moot. It is expected *a priori* that the imposition of BTA's on non-signatories would have some inducement effect on abatement efforts in those countries, provided their efforts were rewarded with a reduction in the BTA's. Just how much of an inducement effect – in particular whether it is in the interest of the country to become a full member of the coalition – is an empirical question. The literature cited above provides some reason for optimism on this topic (e.g. Bohringer et al. 2011, Hubler 2011, Lessmann et al. 2009, Winchester 2011).

Fifth, the political-economy argument in favour of using embodied carbon BTA's to protect domestic industries remains unaffected by considerations of welfare optimality. The political economy argument is particularly salient in the case of small open economies, since there is no aggregate welfare benefit to be obtained in such economies by the use of border adjustments. But in this case, the formal link between the value of BTA that is necessary to protect competitiveness and embodied carbon is very weak. The embodied carbon of domestic goods determines the value of the emissions tax placed on those goods. Therefore embodied carbon entails higher costs for domestic firms ceteris paribus. However, there are also general equilibrium effects that may either reinforce or offset some of these cost increases. Depending on how one defines competitiveness, the value of the required BTA may be significantly different from the embodied carbon value.

IV. Conclusion

The paper has derived formulas for the optimal choice of BTA's for a coalition of cooperating countries, under an exogenous emissions reduction target. The distinction between a global and domestic target is of prime importance. Under a domestic target, the optimal BTA is determined by a terms of trade effect only, and therefore there is no welfare justification for a carbon based BTA in this case. It follows that most policy modelling papers have used the wrong baseline (constant domestic target) to test the effectiveness of carbon based BTA's, at least from the perspective of welfare economics. In contrast, under a global target, the optimal BTA consists of the standard two components derived from earlier theoretical literature: first the terms of trade component and second an induced foreign emissions component. Both versions of the formula (domestic and global target), show that there is an asymmetry between the treatment of imports and exports.

Reflection on the results suggests that the focus of the modeling literature on carbon leakage as a major policy concern may have been misplaced. Under both domestic and global targets, leakage represents the optimal rearrangement of production patterns, from the perspective of the coalition, in order to meet the target in the least-cost manner. This rearrangement reflects the interaction of the environmental policy tools (domestic carbon price and BTA's) with the comparative advantages of countries inside and outside the coalition. It may be of interest to show how this rearrangement of production changes as the membership of the coalition changes, but this dimension of the problem not been taken up by economists to date.

At the same time, there are serious practical limitations to the implementation of the optimal BTA formula, in terms of trade legality and computational feasibility. As a result, a BTA based on domestic embodied carbon is probably the only option that satisfies international trade rules and is computationally feasible. Unfortunately, this approach takes us far away from the theoretical ideal. Whether embodied carbon BTA's are welfare improving for the coalition is an empirical question, whereas the optimal BTA is welfare improving by construction.

In any case, focusing on a static framework in which the membership of the coalition is fixed probably misses the most important potential effect of BTA's, which is to encourage non-abating countries to join the coalition by adopting emission policies of their own. In this case, the link between the proposed BTA and the theoretical optimum is not particularly important, since success takes the form of global compliance and the BTA is not actually imposed. Further modeling work is required to assess the likelihood of this outcome.

Finally, the political economy argument for BTA's, based on the competitiveness of domestic firms, is not affected by considerations of general social welfare. Depending upon how competitiveness is defined (e.g. maintaining market share), the BTA required in this context may bear little relation to either the optimal value or the embodied carbon BTA, since there are likely to be significant general equilibrium effects following the imposition of a domestic climate policy. Specifically, to the extent that foreign and domestic goods are only imperfectly substitutable, domestic firms will be able to pass part of the cost increase on to consumers and therefore they will require less protection than the embodied carbon measure indicates. Therefore, it is important to be clear whether a proposed BTA policy is motivated by a concern for social welfare or by competitiveness of domestic firms, since the two concerns are likely to bear little relation to each other.

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