Reflections on Carbon Leakage[*]

Larry Karp[†]

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Abstract

The general equilibrium effects of stricter environmental policy might reinforce or moderate the partial equilibrium effects. In some cases, the general equilibrium effects can overwhelm the partial equilibrium effects, leading to negative leakage. A partial equilibrium model helps to assess the likely magnitude of leakage, and the magnitude of border tax adjustments needed to offset it. I discuss recent simulation and econometric papers that attempt to measure leakage and the effects of border tax adjustments

Keywords: carbon leakage, border tax adjustment, trade and the environment, environmental policy.

JEL classification numbers C72, H4, Q54

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[†]Department of Agricultural and Resource Economics, University of California, Berkeley, and the Ragnar Frisch Center for Economic Research, email: karp@berkeley.edu

1 Introduction

Tighter environmental regulations increase production costs in dirty industries. If trading partners follow Business as Usual (BAU), the relatively higher production costs of environment-intensive ("dirty") goods in the regulating country may shift the production of those goods to the countries that do not regulate. This shift raises emissions in the non-regulating countries, possibly undermining the environmental objectives of the regulating country and increasing job losses there. This concern is the basis for the pollution haven hypothesis, which lies behind much of the literature on trade and the environment. "Carbon leakage", defined as the number of units of increased carbon emissions in non-regulating countries, per unit of decreased emissions in the regulating countries, is an important example of the trade and environment nexus. I examine both general and partial equilibrium models of leakage, then review the empirical/simulation findings from this literature, and then discuss policy implications.

Broad and effective climate policy may affect factor prices, making a general equilibrium model appropriate for determining the magnitude of leakage and of border tax adjustments (BTAs) needed to offset leakage. However, partial equilibrium models show more clearly the relation between parameter values and these magnitudes. Partial equilibrium models are also convenient for back-of-the-envelope calculations that help to suggest plausible ranges of leakage and border tax adjustments. Because one type of model is probably more accurate, but the other is certainly easier to work with, I begin be considering the relation between the two. I address two questions: (1) Does a partial equilibrium model (i.e. one that ignores changes in factor prices) understate or overstate the true magnitude of leakage? (2) Taking into account changes in factor prices, can leakage be negative?

These questions are somewhat more involved than they appear. General equilibrium models, unlike partial equilibrium models, respect full-employment and balanced-trade conditions. We do not obtain a partial equilibrium model simply by "turning off" adjustments in factor prices. Because a partial equilibrium model is (usually) not a special case of a general equilibrium model, one has to be careful in defining what it means for one model to understate or overstate the magnitude of leakage, relative to the other model.

In order to answer the second question, one must know whether stricter regulation causes a country's net import demand function for the dirty good to shift down or up. If stricter regulation causes this import demand function to shift up, then for any world price the country's net imports of the dirty good increase, causing trading partners' production of that commodity and emissions to increase.[1] These increased emissions are leakage. If stricter regulation causes the country's net import demand for the dirty good to shift down, trading partners' production of that good falls, as does their emissions. In this case, leakage is negative.

After considering leakage in a general equilibrium setting, I analyze a simple partial equilibrium model that builds in the assumption that leakage is positive. This model leads to an explicit relation between the magnitude of leakage and a few parameters. Although lacking direct measures of some of those parameters, we might have a sense of their plausible magnitude. We can then at least get a feel for likely magnitudes of leakage, and understand the effect of parameter values on that estimate. By choice of parameters it is possible to produce large estimates of leakage, but for a range of parameters that seem reasonable, I find that leakage is less than 20%. This kind of back-of-the-envelope calculation may provide a useful prelude to consideration of CGE models. I also use the partial equilibrium model to examine the magnitude of different types of BTAs.

2 General equilibrium and leakage

Here I consider two general equilibrium models. The first is a Heckscher-Ohlin-Samuelson (HOS) model and the second has a Ricardian flavor. Both of these models contain a clean sector y and a dirty sector x, with the relative price of the dirty good denoted as p. The clean sector uses capital and labor to produce the clean good. The dirty sector uses capital and labor, producing x and emissions, z. There is no trade in factors. The supply of capital and labor is fixed, and their prices r,w, endogenous; the level of the emissions tax, t, is exogenous, and emissions are endogenous. Both sectors produce with constant returns to scale (CRTS). I also assume that preferences are homothetic.

These assumptions imply that, conditional on the tax, the relative demand and supply functions (i.e. the supply and demand of good x relative to good y) depends only on the relative commodity price, p as Figure 1 shows.

[1] If the country exports the dirty good, an upward shift in its *net* import function for the dirty good leads to a fall in its exports, again causing an increase in trading partners' production of this commodity.

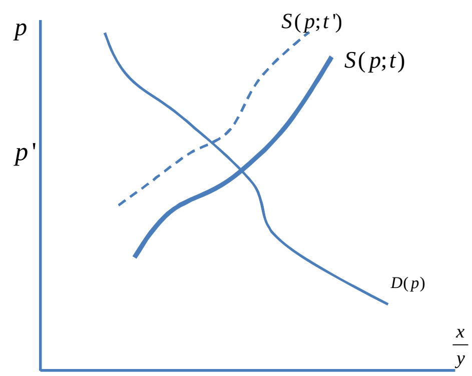

Figure 1: The relative supply and demand curves under two levels of emissions tax, $t' > t$. p' is the equilibrium relative price under t'

The CRTS assumption means that marginal costs are constant at given factor prices. Starting with some level of the emissions tax (possibly zero), there is a corresponding autarchic equilibrium consisting of prices p, w, r. Suppose that we hold the factor prices constant and increase the emissions tax to t'. In order to maintain zero profits in both sectors, at constant factor prices, the relative price of the dirty good must rise, say to p^*. If we allow factor prices to adjust, following the increase in the emissions tax, there will be a new equilibrium relative price, say p', that also maintains zero profits in both sectors. If $p^* > p'$, I say that the partial equilibrium estimate of leakage overstates the actual level, where "actual" means "when factor prices adjust". If the inequality is reversed, I say that the partial equilibrium estimate of leakage understates the actual level.

The basis for this interpretation is that leakage most obviously occurs because a higher emissions tax increases production costs. Under CRTS, marginal production costs are constant for given factor prices. Zero profits requires that price equals unit production costs. The higher is the price needed to keep profits in the dirty sector from becoming negative, the greater is the domestic cost increase, and the greater is the incentive for production of the dirty good to take place abroad. For both the HOS and the Ricardian model, it is a simple matter to compare the price increase (due to the higher tax) needed to maintain zero profits in both sectors, with and without adjustments of factor prices. Therefore it is easy to determine whether a partial equilibrium estimate of leakage understates or overstates leakage.

In a partial equilibrium setting, a tax increase raises production costs and shifts in the domestic supply curve, without altering the demand curve. The higher tax therefore shifts out the partial equilibrium excess demand curve, shifting production of that good abroad, leading to (positive) leakage. Positive leakage is inherent in any sensible partial equilibrium model. In such a model, the question is the magnitude, not the sign, of leakage.

It is more challenging to determine whether leakage is positive in a general equilibrium setting. Two issues arise here. The relatively simple issue is whether the higher tax increases the autarchic relative price of the dirty good, p, as occurs in Figure 1. Copeland and Taylor (2003) and Krishna (2010) find that in the HOS setting, stricter regulation increases the country's autarchic relative price. However, their conclusion rests on a particular assumption about the production function in the dirty sector. The conclusion can be reversed under a more general and still plausible production function, as Section 2.1 shows.

The price intercept of a country's import demand function for the dirty good equals the autarchic price. The direction of change of the import demand function (for the dirty good) is the same as the direction of change of the autarchic price, *in the neighborhood of the autarchic price*. If the price at which the country trades happens to be in this neighborhood, i.e. if the volume of trade is negligible, then indeed leakage is positive if and only if the higher tax increases the autarchic price. Most of the previous literature seems to have stopped at this point.

The second and more complicated issue arises because general equilibrium models respect the balance of payments constraint. The balance need not be zero, but we do not want a result that is driven by a change in the balance of payments. Because we hold the balance of trade constant, there is no loss in generality in assuming that it is zero.

Figure 2 shows a situation where, facing relative price p and an emissions tax t, a country's equilibrium production point is at a. The line labelled $BOP\,(p;t)$ shows the country's Balance of Payments constraint. This constraint depends on the tax because the tax affects the location of the production point, a. The line $IEP(p)$ is the country's Income Expansion Path, a straight line because of the assumption of homothetic preferences. The consumption point is b and the trade triangle, Δabc, shows the level of imports in the initial equilibrium as the length of the side cb, $\parallel cb \parallel$. The price

p and the magnitude $\parallel cb \parallel$ are the coordinates of a point on the country's import demand function, at the initial tax.

We want to know whether the tax increases or decreases import demand at this price. The dashed line shows the set of points where relative production of the dirty and clean good equals the ratio at point a. In moving Southwest along this line, the percentage contraction in both sectors is equal. At any point above the dashed line, $\frac{x}{y}$ is smaller than at point a, and conversely for points below the dashed line.

An increase in the tax, and the resulting reduction in emissions, decreases the productivity of factors in the dirty sector. The higher tax therefore reduces real income, putting aside any gains from the cleaner environment. The new consumption point must therefore lie on a lower BOP curve, e.g. on $BOP(p;t')$ at point b. By construction, the triangle $\Delta a'b'c'$ is identical to Δabc. It is obvious from the property of congruent triangles that point a' must lie above the dashed line, i.e., Northwest of point d.

If the actual production point lies Northwest of a' (on $BOP(p,t')$) then the dirty sector has contracted more than the clean sector: the relative production $\frac{x}{y}$ has fallen. In this case, the level of imports has increased at the original price p: imports exceed $\parallel cb \parallel$. In this situation, the higher tax has shifted out the import demand curve for the dirty good, just as in a partial equilibrium model; leakage is positive. However, if the actual production point lies Southeast of a' (on $BOP(p,t')$) then the higher tax causes the import demand function for the dirty good to shift in, leading to negative leakage. Point a' is difficult to identify in a general setting, so instead I summarize the results in terms of point d:

Remark 1 *Assume that preference are homothetic. A necessary condition for a higher tax to shift out the import demand for the dirty good (leading to positive leakage) is that the tax causes the ratio of production $\frac{x}{y}$ to fall, i.e. production occurs above point d. A sufficient condition for the higher tax to shift in the import demand for the dirty good (leading to negative leakage) is that the tax causes the ratio of production $\frac{x}{y}$ to rise, i.e. production occurs below point d.*

This result depends on homotheticity of demand, but not on specifics of the production side of the economy. Note also that the condition for positive leakage is necessary, whereas the condition for negative leakage is sufficient.

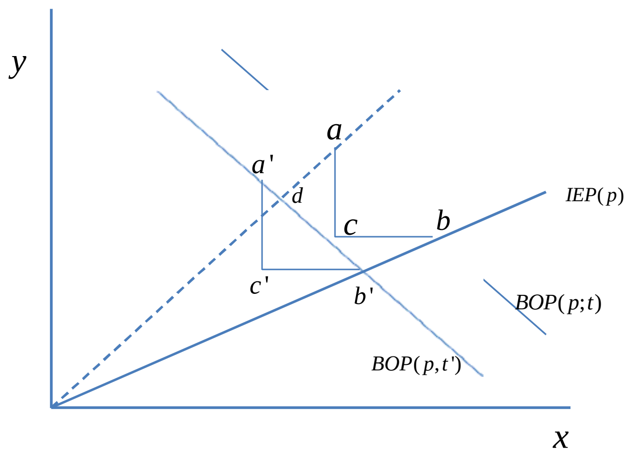

Figure 2: The balance of payments constraint before and after the increase in emissions tax.

2.1 A Heckscher-Ohlin-Samuelson model

I invert the joint production function in the dirty sector to write out of the dirty good as a function of capital, labor and emissions. The unit cost function of the clean sector is $c_y(w, r)$ and the unit cost function of the dirty sector is $c_x(w, r, t)$. The envelope properties of the unit cost functions imply:

$$\begin{array}{ccccc} \dfrac{\partial c_x}{\partial w} & = & a_{xL} & \dfrac{\partial c_x}{\partial r} = a_{xK} & \dfrac{\partial c_x}{\partial t} = a_{xz} \\ \dfrac{\partial c_y}{\partial w} & = & a_{yL} & \dfrac{\partial c_y}{\partial r} = a_{yK}, & \end{array}$$

where a_{ij} is the amount of factor $j \in$ {capital, labor, emissions} used to product one unit of output in sector $i \in \{x, y\}$. The zero profit conditions are

$$c_y(w, r) = 1 \text{ and } c_x(w, r, t) = p.$$

Figure 3 graphs the zero profit conditions for a given emissions tax, t, and commodity price p. For this tax, the combination of w, r that is consistent with zero profits in both sectors is at point a. The tangent of the y isocost curve is steeper than the tangent of the x isocost curve, indicating that

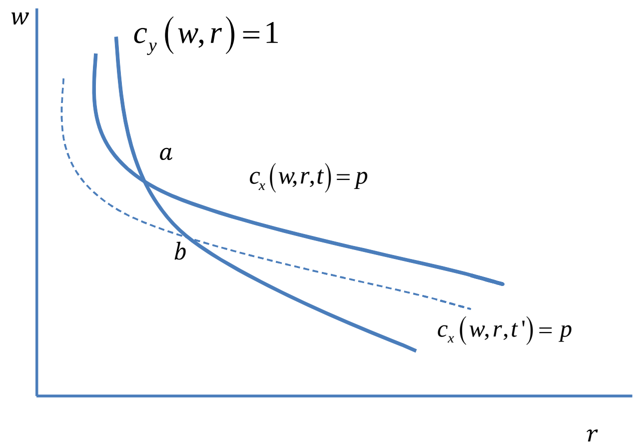

Figure 3: Graphs of zero profit conditions when the clean sector is relatively capital intensive.

the clean sector is relatively capital intensive at this factor price. The assumption that the clean sector is relatively capital intensive is unimportant.

Holding p constant, a higher tax, $t' > t$, increases the production costs in the dirty sector, causing the 0-profit isocost curve to shift down (the light dashed curve) so that the new equilibrium factor price at the original commodity price is at b. The higher tax raises the cost of capital and lowers the wage. In a closed economy or in a large open economy, the change in t changes the equilibrium value of p.

This figure shows that the general equilibrium effect, operating through changed factor prices, moderates the partial equilibrium effect of a higher environmental tax. At point b, the dirty sector maintains zero profits without any rise in the commodity price. Here, the change in factor prices completely offsets the change in the tax, so that production costs remain constant. With constant factor prices, in contrast, there would be negative profits at the original commodity price and the higher tax. If factor prices were fixed, the higher tax would have to induce a large increase in p to sustain zero profits in the dirty sector, reflecting the large cost increase there. If both commodity prices and factor prices can adjust, the factor prices adjust in the direction shown, partially offsetting the higher production costs caused by the higher tax. The adjustment of factor costs therefore entails a smaller increase in

p, reflecting the smaller increase in production costs (relative to the partial equilibrium setting where factor prices are constant). In summary:

Remark 2 *The change in factor prices moderates the higher relative cost of the dirty good, resulting from the higher emissions tax. In this respect, the general equilibrium effects moderate the partial equilibrium effect of the higher tax, and a partial equilibrium model overstates the magnitude of leakage.*

Without more structure, it is not possible to determine whether a higher tax creates (positive) leakage. The difficult arises because it is not easy to identify point a' in Figure 2. Therefore, I consider the simpler question: Does a higher tax shift in or out the relative supply $\frac{x}{y}$, for a fixed relative commodity price? Answering this question requires knowing whether production occurs above or below point d in the figure. From Remark 1, a necessary condition for leakage to be positive is that at the initial commodity price $\frac{x}{y}$ falls with the higher tax, and a sufficient condition for negative leakage is that $\frac{x}{y}$ rises.

The economy's capital/labor ratio is k. Using the full employment conditions, the relative supply of the dirty good, $\psi\left(p,t;w\left(p,t\right),r\left(p,t\right)\right)=x/y$, is

$$\psi\left(p,t;w\left(p,t\right),r\left(p,t\right)\right)=\frac{a_{yk}-ka_{yL}}{ka_{xL}-a_{xK}}=\frac{a_{yL}}{a_{xL}}\left(\frac{k_y-k}{k-k_x}\right)>0,$$

where k_x and k_y are the capital/labor ratios in the two sectors. The relative supply ψ depends on the relative commodity price and the tax. These two variables determine the factor prices. To determine whether a higher tax shifts the import demand function in or out, I evaluate the sign of $\frac{\partial\psi}{\partial t}$ and use Remark 1.

Holding the commodity price fixed and differentiating with respect to the tax, I obtain

$$\frac{\partial\psi}{\partial t}=A+B,\ \text{with} \tag{1}$$

$$A\equiv a_{xL}\left[\frac{k-k_x}{\left(a_{xL}k-a_{xK}\right)^2}\right]\left(\frac{da_{yK}}{dt}-\frac{da_{yL}}{dt}k\right)\leq 0\ \text{ and}$$

$$B\equiv\left[\frac{a_{yL}a_{xK}}{t\left(a_{xL}k-a_{xK}\right)^2}\left(k_y-k\right)\right]\left(\eta_{xK}-\frac{k}{k_x}\eta_{xL}\right).$$

The last expression uses

$$\eta_{xK}=\frac{da_{xK}}{dt}\frac{t}{a_{xK}}\quad\text{and}\quad\eta_{xL}=\frac{da_{xL}}{dt}\frac{t}{a_{xL}},$$

the elasticities of unit factor requirements in sector x, with respect to the tax (holding commodity price fixed, but allowing factor prices to adjust).

Expression A is non-positive, and strictly negative when the elasticity of substitution between inputs in the clean sector is positive. The first term in A is positive because sector x is relatively labor intensive ($k > k_x$). As Figure 3 shows, a higher tax induces a higher rental rate to wage ratio, $\frac{r}{w}$. This change in relative factor prices causes the clean sector to switch to a more labor intensive process. The increase in $\frac{r}{w}$ means that each unit of production uses less capital and more labor, i.e. $\frac{da_{yK}}{dt} \leq 0 \leq \frac{da_{yL}}{dt}$ which in turn implies that $A \leq 0$; the equalities are strict except in the limiting case of Leontieff production, where the factor mix is independent of factor costs, in which case $A = 0$.

Signing the term B is not so straightforward. The term in square brackets on the right side is positive because of the assumption that the clean sector is relatively capital intensive. However, the sign of the second term, in parenthesis, is ambiguous in general. The higher emissions tax induces the dirty sector to pollute less. The decreased level of emissions means that production of one unit of the dirty good is no longer feasible at the initial level of capital and labor. At least one of the factors, and possibly both, increase per unit of output of the dirty good. In general we cannot rule out the possibility that both $\eta_{xK} > 0$ and $\eta_{xL} > 0$.

If the dirty sector production function is separable, as previous papers assume, then output can be written as $x = F\left(z, h\left(K_x, L_x\right)\right)$ for some function h, which is positive and increasing in both arguments. The assumption that F has constant returns to scale implies that h also has constant returns to scale, and therefore is homothetic. Let z_1 be the optimal level of emissions per unit of output under the original tax, and $z_2 < z_1$ be the optimal level of emissions under the higher tax. Let h_i be the level of h necessary to produce one unit of the dirty good when $z = z_i$, i.e. h_i solves $F\left(z_i, h_i\right) = 1$. Thus, $h_2 > h_1$.

Figure 4 shows: the "h isoquants" for two levels $h_2 > h_1$; the equilibrium relative factor prices, $\left(\frac{w}{r}\right)_1$ and $\left(\frac{w}{r}\right)_2$ corresponding to the lower and the higher tax, respectively; and the corresponding production points, a and b. At the higher tax and lower wage/rental ratio, the amount of labor per unit of output, a_{xL}, has unambiguously increased, and a_{xK} might have either increased or decreased. However, it is clear that the proportional increase in a_{xK} must be less than the proportional increase in a_{xL}, implying that

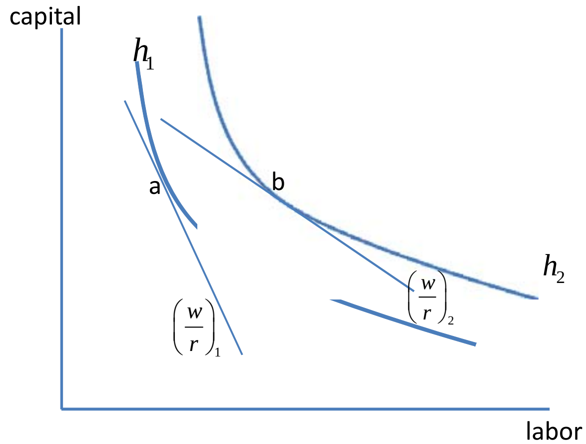

Figure 4: Following a higher emissions tax, the percentage increase in labor per unit of the dirty good is greater than the percentage increase in capital per unit of the dirty good.

$\eta_{xK} - \eta_{xL} < 0$.[2] This inequality and the fact that $\frac{k}{k_x} > 1$ implies that $B \leq 0$. Again, the inequality is strict unless h is Leontieff.

Thus, in the case where the production function in the dirty sector is separable in emissions and in the combination of capital and labor, a higher emissions tax necessarily shifts in the relative supply of the dirty good (unless production of both the clean and the dirty good are Leontieff). With homothetic preferences, an increase in the tax shifts in the relative supply $\frac{x}{y}$, satisfying the necessary condition for leakage to be positive. In summary:

Remark 3 *If the production function is separable in emissions and in the combination of capital and labor, then a higher emissions tax lowers the country's comparative advantage in the dirty good, satisfying the necessary condition for positive leakage. Leakage is positive if the higher tax causes a large*

[2]A straight line through the origin and point a gives the set of capital and labor requirements at different levels of h for the same factor price ratio. This line passes through the curve h_2 at a point to the North West of b; denote that point as c (not shown in Figure 4). At points a and c the capital/labor ratios are constant, so in moving from a to c the proportional increase in capital equals that of labor. Since point b lies to the South East of point c, the movement from a to b involves a higher proportional increase in labor than in capital.

relative shift from the dirty to the clean sector.

If the separability assumption does not hold, then it is possible for the general equilibrium effect to oppose and overwhelm the partial equilibrium effect. For example, suppose that the elasticity of substitution between capital and labor in the clean sector is small, so that $A \approx 0$.[3] Ignoring that term, equation (1) implies

$$\frac{\partial \psi}{\partial t} > 0 \Longleftrightarrow \eta_{xK} - \frac{k}{k_x}\eta_{xL} > 0. \tag{2}$$

It is possible that a higher emissions tax and resulting fall in emissions leads to such a large increase in capital intensity in the dirty sector that the amount of labor per unit of production actually falls. In that case ($\eta_{xL} < 0$) inequality (2) holds. In a more plausible situation, both unit labor and capital requirements in the dirty sector increase with the fall in emissions. In that case, inequality (2) requires that

$$\frac{\eta_{xK}}{\eta_{xL}} > \frac{k}{k_x} > 1.$$

That is, to obtain the counter-intuitive result it is not enough that the percentage increase in capital exceeds the percentage increase in labor per unit of dirty output; the former must exceed the latter by more than the ratio of the economy-wide capital labor ratio to the dirty sector capital labor ratio. In summary:

Remark 4 *If the production function in the dirty sector is not separable in emissions and a composite of capital and labor, and if in addition the elasticity of substitution between inputs in the clean sector is low, then an increase in the emissions tax can promote a country's comparative advantage in the dirty sector. In this case, the higher tax creates negative leakage.*

[3] This extreme example helps to shed light on the general equilibrium effects. However, it is well known that if there is a significant difference in the elasticities of substitution in the two sectors, then there will be factor intensity reversals over some range of prices. This complication might be worth exploring, but it does not appear central to the issue at hand.

2.2 A Ricardian model

Chau (2003) constructs a model with three sectors, producing two tradable goods, the dirty and the clean goods, and non-tradable abatement services. One unit of abatement services removes one unit of pollution. Chau uses Cobb Douglas functional forms, but general functional forms make the mechanism more transparent, and easier to compare with the results above.

There are constant returns to scale in each sector, and two factors of production, capital and labor. Here there are three sectors and two factors of production. This "imbalance" is reminiscent of the textbook Ricardian model, where there are two sectors and one factor. In that setting, under incomplete specialization, technology determines the equilibrium relative commodity price. There is a similar result here: the assumption of incomplete specialization, together with an exogenously chosen emissions tax, determines the equilibrium autarchic relative commodity price between the two tradeable goods, p, independent of preferences.

In this setting, the relative supply of tradables is discontinuous in the commodity price. In an equilibrium with trade, the economy is completely specialized in one of the two tradable goods unless the world price equals the country's autarchic price, a function of the tax. This discontinuity probably makes the model less descriptive than the HOS model. Nevertheless, there are two reasons for considering this model. First, it shows that the general equilibrium effects do not always moderate the partial equilibrium effects of a higher tax, in the sense used in Remark 2. Second, it provides another simple example of the counter-intuitive situation where a higher emissions tax promotes a country's comparative advantage in the dirty sector.

At constant factor prices, the imposition of a sufficiently large tax causes the firm in the dirty sector to incur abatement costs. To the extent that the firm continues to emit pollution, it also has to pay taxes. Both of these effects decrease revenue net of abatement costs and tax payments. If factor costs were to remain constant, the relative price of the dirty good has to rise in order to maintain 0 profits in the dirty good sector. This partial equilibrium response to stricter environmental policies increases the relative price of the dirty good.

In the general equilibrium setting, the tax changes factor prices. For concreteness, suppose that the dirty sector is the most labor intensive of the three sectors, and the abatement sector is the most capital intensive of the three. The imposition of the tax creates the demand for abatement, which requires relatively large amounts of capital. This increased demand for capital tends to increase the price of capital relative the price of labor. Because (by assumption) the clean sector is capital intensive relative to the dirty sector, this change in factor prices raises costs in the clean sector by more than in the dirty sector. In order to maintain 0 profits in all sectors, this change in costs causes pressure for the price of the clean good to rise relative to the price of the dirty good.

In this example, the general equilibrium effect moderates the partial equilibrium effect, and can even overwhelm it. When that occurs, the emissions tax promotes the country's comparative advantage in the dirty good, leading to negative leakage. However, unlike in the HOS model above, here it is possible that the general equilibrium effect reinforces the partial equilibrium effect.

As in the previous section, the clean sector produces the numeraire good and creates no emissions. In the absence of abatement, the dirty sector produces one unit of emissions per unit of output. The relative price of the dirty good is p. The firm in the dirty sector can remove a unit of emissions by buying a unit of "abatement services" at price p^A, and the firm faces a unit emissions tax of τ. Profits in the dirty sector equal revenues minus tax payments minus payments to labor and capital minus the cost of abatement services. If the firm buys A units of abatement services, its profits are

$$\begin{aligned}\pi_x &= px - \tau\,(x - A) - wL_x - rK_x - p^A A \\ &= x\,(p - \tau) - wL_x - rK_x + \left(\tau - p^A\right) A.\end{aligned} \tag{3}$$

Suppose that in equilibrium the firm abates at a positive level but does not eliminate emissions: $0 < A < x$. This assumption, together with profit maximization, requires that in equilibrium

$$\tau = p^A. \tag{4}$$

If this equality did not hold, the firm would either choose not to abate, or would abate all emissions.

The cost of producing one unit of output in sector $i = x, y, A$ (the dirty, clean, and abatement sectors, respectively) is $c_i(w, r)$. The assumption that all sectors operate, means that there must be 0 profits in each sector and the equilibrium condition (4) must hold:

$$\tau = c_A(w, r) \quad 1 = c_y(w, r) \quad p - \tau = c_x(w, r, \tau). \tag{5}$$

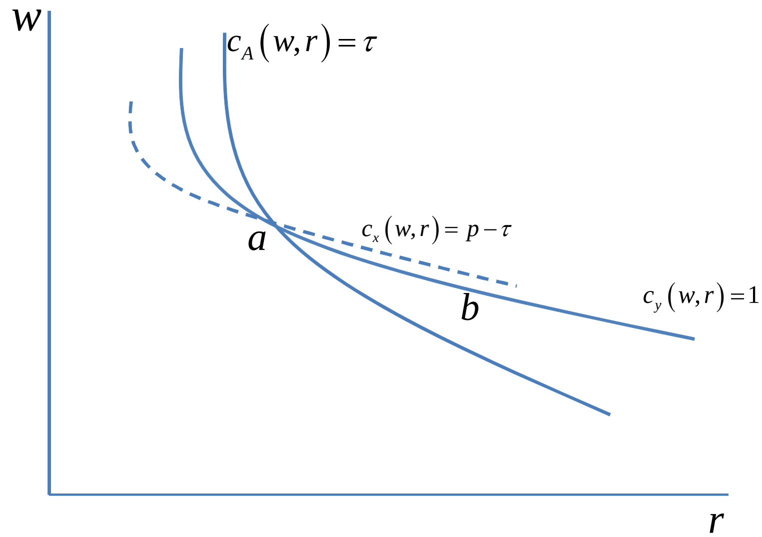

Figure 5: Zero profits for three sectors with incomplete specialization. The abatement sector is most capital intensive and the dirty sector is least capital intensive

This system contains three equations in three unknowns, w, r and p; under incomplete specialization, the unique solution determines the relative price of tradables, as in the Ricardian model.

Figure 5 shows the zero-profit isocost curves for the numeraire good ($c_y = 1$) and for abatement services ($c_A = \tau$), for a fixed τ. The equilibrium factor price is at point a. The figure embodies the assumption that the abatement sector is more capital intensive than the clean sector. An increase in the emissions tax would cause the isocost curve for abatement services to shift out, causing the equilibrium factor prices to move along the $c_y = 1$ curve toward point b. The isocost curve for the dirty good sector (the dashed curve, $c_x = p - \tau$), shows the price that is consistent with incomplete specialization. It is the price that causes the three curves to intersect at a single point, a in the figure. At any other value of p the three curves do not intersect at the same point. In that case, there is no solution to the system (5): for such a price, there is not an equilibrium in which all three sectors operate. The flatter slope of the curve $p - \tau = c_x$ indicates that the clean sector is more capital intensive than the dirty sector.

An increase in τ causes the equilibrium factor prices to move in the direction of point b as explained above. In order to maintain incomplete specialization, p must also change so that the three curves intersect at the new equilibrium factor price. The direction of change of p following an increase in τ is not obvious from the figure. It is clear that $p - \tau$ must fall in order for the dashed curve to pass through the new equilibrium factor price, but that fact does not tell us whether p increases or decreases following an increase in τ.

In order to determine the comparative statics, I totally differentiate the system (5) and manipulate the resulting system to obtain the expression for the change in the price needed to retain incomplete specialization:

$$\frac{dp}{d\tau} = 1 - \left(\frac{a_{xL}}{a_{AL}}\right) \frac{k_y - k_x}{k_A - k_y}. \tag{6}$$

At constant factor prices, a unit increase in the tax requires a unit increase in the commodity price in order to maintain 0 profits in the dirty sector (under incomplete specialization). The first term (1) of the comparative statics expression, equation (6), reflects this partial equilibrium effect. The second term can be positive or negative, depending on the sign of $\frac{k_y - k_x}{k_A - k_y}$. If this expression is negative, the general equilibrium effects reinforce the partial equilibrium effect. If this expression is positive, the general equilibrium effect tends to offset the partial equilibrium effect. In summary

Remark 5 *The general equilibrium effect moderates the partial equilibrium effect if and only if sign* $(k_y - k_x) =$ *sign* $(k_A - k_y)$. *For* $\frac{a_{AL}}{a_{xL}} < \frac{k_y - k_x}{k_A - k_y}$, *the general equilibrium effects oppose and overwhelm the partial equilibrium effect, leading to negative leakage. In the limiting case where the dirty sector and the abatement sector use the same capital labor ratio, the general equilibrium effect reinforces the partial equilibrium effect:* $\frac{dp}{d\tau} = 1 + \frac{a_{xL}}{a_{AL}} > 1$.

2.3 A comparison

In the HOS setting, the general equilibrium effect moderates the partial equilibrium effect of stricter environmental policies. The higher tax increases costs in the dirty sector. When factor prices adjust, they do so in a way that decreases costs in the dirty sector, moderating the partial equilibrium effect. In the Ricardian setting, a higher tax increases the price received for abatement services, increasing the relative price of the factor used intensively in that sector. If, for example, the abatement sector is relatively capital intensive, the higher tax leads to a higher rental/wage ratio. If the dirty sector is more capital intensive than the clean sector, this change in factor prices increases labor and capital costs in the dirty sector more than in the clean sector, thus reinforcing rather than moderating the partial equilibrium effect. When the clean sector is more capital intensive than the dirty sector, the general equilibrium effect moderates the partial equilibrium effect.

In both the HOS and the Ricardian setting, the general equilibrium effect may overwhelm the partial equilibrium effect. When that occurs, stricter environmental policies increase a country's comparative advantage in the dirty good, and lead to decreased emissions elsewhere (negative leakage).

For this counter-intuitive result in the HOS setting, the higher tax must cause the relative production of the dirty good to fall only slightly or increase. If production is separable, then we can think of the dirty firm as using capital and labor to produce the joint products, "potential output" and emissions, and then using a fraction of potential output to reduce emissions. The two activities, production and abatement, are the same, in that they both use the same capital labor ratio. With non-separable production in the dirty sector, this kind of two-stage process does not occur. A reduction in emissions is fundamentally different than using up some "potential output" to abate, because a reduction in emissions leads to a different capital labor ratio, even in the absence of changes in factor prices.

In the Ricardian model, production of the dirty good and abatement are literally different activities, and therefore naturally have different capital labor ratios. There, the general equilibrium effect moderates the partial equilibrium effect if and only if the capital labor ratio in the clean sector lies between the ratios in the dirty sector and the abatement sector. If (for example) the dirty sector is much less capital intensive then the clean sector, which is only slightly less capital intensive than the abatement sector, then the general equilibrium effect overwhelms the partial equilibrium effect. In this example, the increased demand for capital caused by higher abatement takes resources chiefly from the clean sector, leading to a relative expansion of the dirty sector. If the dirty sector and the abatement sector in the Ricardian model have the same capital labor ratios – as is implicitly the case in the HOS model with separable production – then the general equilibrium effect reinforces the partial equilibrium effect.

3 A partial equilibrium model

A general equilibrium model is probably appropriate for studying the effects of broad climate policy. However, these models do not tell us much about the magnitude of leakage, unless we move to a CGE framework. The partial equilibrium assumption that factor prices do not adjust to environmental policies provides a good approximation in many cases, although probably not for climate policy. However, the partial equilibrium model helps reveal the relation between parameters and results, and it makes it easy to do back-of-the-envelope calculations of the magnitude of leakage. This kind of information is useful when confronting CGE models, where the relation between assumptions and outcomes is not transparent.

The previous section shows that the general equilibrium effects always moderate the partial equilibrium effects in the HOS setting, and "often" in the Ricardian setting. Moreover, a partial equilibrium model builds in the assumption that leakage is non-negative, whereas with a general equilibrium model leakage can be negative. These results suggest that a partial equilibrium model is "likely" to provide an upwardly biased estimate of leakage, and the bias may be large. The results are no more than suggestive, however, because the partial equilibrium model need not be a special case of the general equilibrium model. Indeed, in the partial equilibrium model considered here, the equilibrium supply functions are upward sloping, so production is not constant returns to scale. Despite this caveat, the general equilibrium analysis leads me to think that the partial equilibrium estimate of leakage is more likely to be upwardly than downwardly biased.

In the model here, a group of insiders reduce their emissions, and the remaining countries, the outsiders, follow business as usual. I study two versions of a simple partial equilibrium model of leakage. In both versions, the demand function for the dirty good is the same in all countries. In the first version, with general functional forms, the production costs and thus the carbon intensity and the supply functions can be different between the insiders and the outsiders even before the insiders reduce their emissions. Here I use comparative statics to approximate leakage. Then I use a linear model, for which I calculate the effects of a non-marginal change in insiders' emissions. With this model it is easy to calculate two kinds of border tax adjustments. However, for the linear model I assume at the outset that countries are ex ante identical, i.e. they all have the same supply functions prior to reducing their emissions.

In both cases, producers have increasing marginal production costs, so the supply curves have positive slopes. Stricter environmental policies in one country elicit a supply response elsewhere, only to the extent that the output price changes. In contrast, most CGE models and many partial equilibrium models assume differentiated products and constant returns to scale. In that kind of model, an increase in the price of the regulated good can leave unchanged the price of the unregulated good, and increase the supply of that good because the demand for it shifts out.

3.1 The approximation

There are a total of n countries; m insiders adopt a carbon constraint. Carbon is an input into production of the carbon-intensive commodity. All countries have the same demand function for the carbon-intensive commodity, and there is free trade. Suppose that the m insiders ($j = i$ for "insider") reduce their emissions by the amount de and each of the the $n - m$ outsiders ($j = o$ for "outsiders") respond by increasing their emissions by dE. The approximation for leakage, defined as the aggregate number of units of increased output amongst the outsiders, per unit of decreased output amongst the insiders, is

$$L = \frac{(n-m)\,dE}{mde}.$$

In country $j \in \{i, o\}$, the industry cost function is $C^j(S, E)$, where S is output (supply) of the carbon-intensive commodity in the country and E is emissions in that country, with $C^j_S > 0$ and $C^j_{SS} > 0$ and $C^j_{EE} > 0$. The j index allows the cost functions, and thus the supply functions and the carbon intensity to differ between insiders and outsiders, even before the insiders reduce their emissions. The outsiders choose E to minimize costs, so their level of emissions is given by the condition

$$C^o_E\left(S^o, E^o\right) = 0.$$

where S^o is the outsider's supply of the commodity and E^o is their level of emissions; insiders' emissions, $E^i = e$, is constrained. For a given level of E, the inverse supply function for a country is

$$p = C^j_S\left(S^j, E^j\right), \quad j = i \text{ (insiders) and } j = o \text{ (outsiders)}$$

where p is the common price. The level of E is different for insiders and outsiders, so the two groups have different supply functions even if they have the same cost function. Each country has the demand function $D(p)$, so the market clearing condition is

$$nD(p) = mS^i + (n-m)S^o.$$

Differentiating the market clearing condition with respect to e, the insiders' emissions level, yields an expression for $\frac{dp}{de}\frac{e}{p}$. I then differentiate the equilibrium condition for outsiders' emissions to find the expression for $\frac{dE}{dS^o}$. I use the expressions for $\frac{dp}{de}\frac{e}{p}$ and $\frac{dE}{dS^o}$, together with the definition of elasticity of supply with respect to price, $\phi^o = \frac{dS^o}{dp}\frac{p}{S^o}$, and the elasticity of BAU emissions with respect to output, $\theta = \frac{dE}{dS^o}\frac{S^o}{E}$, and some notation collected in Table 1, to obtain the following approximation of leakage:[4]

$$\begin{aligned} L &= (1-\lambda)\frac{\phi^o\theta\rho s^i}{\lambda\phi^i s^i + (1-\lambda)\phi^o s^o + \eta}\frac{E}{e} \\ &= (1-\lambda)\frac{\theta\rho s^i}{\lambda\frac{\phi^i}{\phi^o}s^i + (1-\lambda)s^o + \frac{\eta}{\phi^o}}\frac{E}{e} \\ &= \frac{\theta\rho\delta(1-\lambda s^i)}{\frac{\eta+\phi^i}{\phi^o} + (1-\lambda s^i)\left(1-\frac{\phi^i}{\phi^o}\right)}. \end{aligned}$$

The second expression, using relative rather than absolute elasticities, may be easier to evaluate. For example, if demand is more elastic than supply, then $\frac{\eta}{\phi^o} > 1$. In addition, other things equal, the ability to choose emissions freely increases the elasticity of supply, so it is reasonable to expect that $\frac{\phi^i}{\phi^o} < 1$.[5]

The third expression shows the effect on leakage of outsiders' and insider's relative carbon intensity, δ.[6] This expression also shows that leakage depends on the fraction of insiders, λ, multiplied by the average production share of an insider, s^i, not on the two share parameters independently.

The elasticity of the estimate of leakage, with respect to δ is 1. If outsiders are more carbon intensive, $\delta > 1$. The example below sets $\delta = 1 = s^o$, i.e. I

[4] Both ρ and θ depend on the cost function, but one is not the inverse of the other. For example, it might be the case that under BAU one unit of output creates one unit of emissions, in which case $\theta = 1$. Unless production happens to be Leontieff, a one unit reduction in the emissions constraint reduces output by less than one unit.

[5] If insiders' and outsiders' cost functions are different, this inequality need not hold.

[6] The third line uses the identity $1-\lambda s^i = (1-\lambda)s^o$.

evaluate the estimate of leakage at a point where the insiders and outsiders are identical before the former reduce their emissions. If, for example, the outsiders are 30%, more carbon intensive then the insiders, then the estimates below should be increased by 30%. The elasticity of the estimate of leakage with respect to s^o is

$$\frac{dL}{ds^o}\frac{s^o}{L} = \frac{1}{1 + \left(\frac{\left(\left(\phi^o - \phi^i\right)(1-\lambda)\right)s^o}{\eta + \phi^i}\right)},$$

which is less than 1 if $\phi^o - \phi^i > 0$. Thus, if the typical outsider produces a smaller fraction of the carbon intensive good than the typical insider ($s^o < 1$), then the estimate below exaggerates leakage.

parameter name	meaning
θ	elasticity of BAU emissions wrt output
η	absolute value of elasticity of demand
ϕ^j, $j = i, o$	elasticity of supply wrt price in country $j = i, o$
ρ	elasticity of output wrt constrained emissions (constant price)
s^j, $j = i, o$	output in country j relative to average output per country
S^j, $j = i, o$ and $\bar{S}$	output in country j and average output per country
$\lambda = \frac{m}{n}$	fraction of countries that constrain emissions
δ	$\frac{\text{outsider's emission intensity}}{\text{insider's emission intensity}} = \left(\frac{E}{S^o}\right) / \left(\frac{e}{S^i}\right)$

Table 1: Notation

By evaluating the approximation at a symmetric equilibrium, where $\delta = s^o = 1$, the expression for leakage simplifies to

$$L^{\mathrm{SYM}} = \theta\rho\left(\frac{1-\lambda}{\lambda\frac{\phi^i}{\phi^o} + (1-\lambda) + \frac{\eta}{\phi^o}}\right). \tag{7}$$

The discussion above explains how a departure from symmetry would affect the estimate of leakage. Equation 7 implies that leakage decreases in the membership ratio, λ and in the elasticity ratios $\frac{\phi^i}{\phi^o}$ and $\frac{\eta}{\phi^o}$ and increases in θ and ρ. The maximum possible level of leakage is $\theta\rho$. Given a range of parameter values, we can calculate the range of leakage for this approximation.

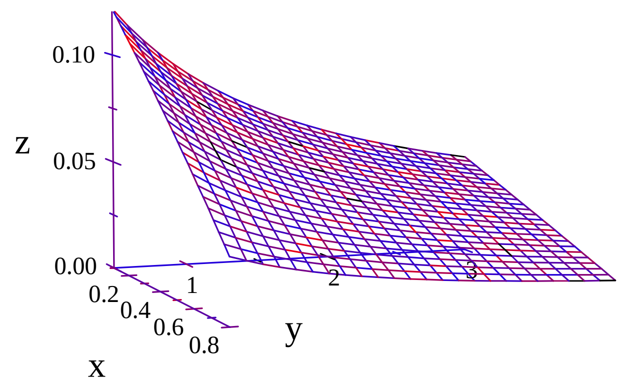

Figure 6: The approximation of leakage: z =leakage, $x = \lambda$, $y = \frac{\eta}{\phi^o}$, $\theta\rho = 0.2$ and $\frac{\phi^i}{\phi^o} = 0.8$

For example, if the carbon intensity under BAU is insensitive to the level of output, then $\theta \approx 1$. If we think that a 10% decrease in the allowable level of emissions leads to a 2% decrease in production of the carbon-intensive commodity then $\rho = 0.2$. If the unconstrained elasticity of supply is 25% greater than the elasticity under the constraint, then $\frac{\phi^i}{\phi^o} = \frac{1}{1.25} = 0.8$. With these guesstimates, we can plot the approximation of leakage evaluated at BAU (the z axis in Figure 6) as a function of λ (shown on the x axis in the figure) and $\frac{\eta}{\phi^o}$ (shown on the y axis in the figure). In this figure, the membership fraction ranges over $(0.1, 0.8)$ and the ratio of demand to supply elasticity $\frac{\eta}{\phi^o}$ ranges over $(0.5, 3)$. Over most of this range, the estimate of leakage is under 10% (well below the maximum level 20% when $\theta\rho = 0.2$) even when the membership ratio is small. I would not present these numbers as a basis for policy advice, but they do suggest reasonable levels of leakage, information that is useful in evaluating CGE models.

The magnitude of the estimate is proportional to $\theta\rho$. For example, if we think that a 10% decrease in the allowable level of emissions results in a 6% decrease in production of the carbon-intensive good (rather than a 2% decrease as the figure assumes), then the estimate of leakage increases by a factor of 3. However, if we think that a larger scale of production leads to less carbon-intensive methods ($\theta < 1$), then the estimate of leakage falls.

3.2 The linear model

The linear model specializes the demand function to be linear and the cost function to be quadratic, leading to a linear supply function. Here I also assume symmetry, i.e. insiders and outsiders have the same cost function in addition to the same demand function. The endogenous variables can be solved in closed form, providing an exact measure of leakage for an arbitrary (rather than infinitesimal) reduction in emissions, and making it easy to examine the effect of policies such as border tax adjustments.

The cost function is

$$K = (a_0 - a_1 E)\, Q + \frac{b}{2} Q^2 + \left(\frac{c}{2} E^2 - c_0 E \right),$$

which I further specialize by setting $a_0 = c_0 = 0$. This specialization implies that the BAU level of emissions is linear in output, $E = \frac{a_1 Q}{c}$ so that BAU emissions per unit of output is a constant $\frac{E}{Q} = \frac{a_1}{c}$; the elasticity of BAU emissions with respect to output is then $\theta = 1$. By choice of units I set $\frac{a_1}{c} = 1$. Costs under BAU (where firms choose E to minimize costs) is

$$K = \frac{1}{2} (b - c)\, Q^2,$$

with $b > c$. The resulting BAU supply function is $Q = \frac{p}{b-c}$, implying that the BAU elasticity of supply with respect to price is $\phi^o = 1$. I assume that the demand function is also linear: $Q = C - Dp$. In this model, the BAU level of emissions per dollar of output equals the inverse of the equilibrium BAU price, $1/p^{\text{BAU}}$. The elasticity of supply, with respect to emissions, evaluated at the BAU level of emissions, is $\frac{c}{b} < 1$.

This model has four "primitive parameters" b, c, C, D. However, by choice of units I can select the positive values of two parameters arbitrarily. In order to make it easier to interpret the results, it is convenient to use elasticities to express the "non-free" parameters. Some calculations show that

$$\begin{aligned} \text{elasticity of demand at unconstrained equilibrium } \eta &= D\,(b - c) \\ \text{elasticity of supply wrt constrained emissions (at BAU) } \rho &= \frac{c}{b}. \end{aligned}$$

These are elasticities evaluated at BAU levels. By choosing units so that the BAU price and level of emissions are both equal to 1, I obtain two more equations that enable me to write the primitive parameters as functions of η, ρ. I carry out the calculations using the primitive parameters and then express the results of interest using the elasticities η, ρ.

If m countries restrict emissions to E, a level that is less than the BAU level, then leakage equals[7]

$$L = \frac{(1-\lambda)\,\rho}{1+\eta-\lambda\rho}. \tag{8}$$

Under BAU, the symmetry assumption means that imports and exports are zero. If the insiders reduce emissions and continue to allow free trade, they begin to import the carbon intensive good. The resulting increased production by outsiders is the source of leakage. The ability to obtain explicit expressions for endogenous variables makes it easy to calculate the effect of different BTAs.

Probably the most aggressive BTA that has been considered charges an outsider a *unit* import tax τ equal to the insider's price of carbon (equal to their marginal cost of abatement) times the amount of carbon contained in each unit of the outsiders' production. If the insiders export the carbon intensive good under this policy, then this BTA is an export subsidy rather than an import tax.

For an exogenous emissions constraint E (less than the BAU level), the insiders' domestic price is $p+\tau$, where p and τ are both endogenous. Under the model assumptions, outsiders' emissions per unit of output is constant, normalized to 1. The equilibrium τ equals insider's marginal abatement cost, which depends on E, p, τ. Solving this implicit equation to write τ as a function of E, p, I can write the supply functions in both the insiders and the outsiders as a function of p; this function equals $Q = \frac{p}{b-c}$ for outsiders and $Q = \frac{p+\tau+cE}{b}$ for insiders. At the equilibrium τ, the right side of these equations are equivalent. The unconstrained producers receive a price per unit of output p. At world price p and unit tariff τ, the constrained producers receive a price per unit of output $p+\tau$. The additional marginal revenue, τ, exactly equals the additional marginal cost; the condition that producers' marginal cost equals the price they receive means that the constrained producers and unconstrained producers face the same marginal condition. Thus, they have the same supply curve, a function of p. This equality does

[7] The formula for leakage in equation (7) collapses to the expression in equation (8) using $\theta = 1 = \phi^o$ and $\rho = 1 - \phi^i$.

not depend on the linearity of the model.

Let insiders' constrained level of emission as a fraction of the BAU level be $r < 1$. The *ad valorem* equivalent of the unit BTA is $t = \frac{\tau}{p}$. The equilibrium ad valorem tax, as a function of the model parameters and the policy variable r, is

$$t = \frac{\tau}{p} = \rho(\eta + 1)\frac{1 - r}{\eta(1 - \rho + r\rho\lambda) + 1 - \rho}. \tag{9}$$

It is straightforward to calculate the comparative statics of this expression with respect to the parameters and the policy variables. For example, $\frac{dt}{dr} < 0$ and $\frac{dt}{d\lambda} < 0$. A weaker policy intervention (a larger value of r) or a larger level of membership (larger λ) both reduce the equilibrium ad valorem BTA.

Figure 7 shows a graph of the "aggressive" equilibrium ad valorem BTA, as a function of the membership fraction $\lambda \in (0.1, 0.8)$ (the x axis) and the policy variable $r \in (0.5, 0.95)$ (the y axis) for $\rho = 0.2$ and $\eta = 1.5$.[8] As insiders cut emissions from 5% ($r = 0.95$) to 50% ($r = 0.5$) the ad valorem tariff rises from a negligible level to approximately 12%. The tax is insensitive to the level of membership.

Leakage under the aggressive BTA is independent of the policy variable r; it equals

$$L^{BTA} = -\rho\eta\frac{1 - \lambda}{(\eta + 1)(1 - \rho) + \rho\eta\lambda} < 0.$$

Here, leakage is negative. Regulation by insiders does not alter the outsiders' supply function. As noted above, the aggressive BTA causes insider producers to have the same supply function as outsider producers, and the latter has not changed. Therefore, the combination of the emissions reduction and the BTA leaves unchanged the supply side of the economy. However, consumers in the insider countries now face the price $(1 + t)p = p + \tau$. The combination of policies therefore shifts in the demand function in insider countries. Because the supply function in those countries is unchanged, the world price falls and is lower than insiders' domestic (consumer) price. Therefore the insider countries begin to export the good; production in all countries falls,

[8] The elasticity of demand for carbon-intensive goods is likely less than 1. However, the analysis of the more general model shows that what matters is the ratio of elasticities of supply and demand. In the linear model here, the elasticity of supply at BAU is fixed to 1 by my decision to set $a_0 = c_0 = 0$. If we think that demand is more elastic than supply, then $\eta > 1$. However, the graph of the BTA under $\eta = 0.8$ is almost identical to the graph in Figure 7.

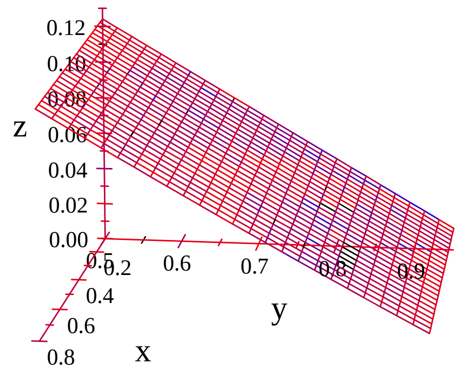

Figure 7: The "aggressive" ad valorem BTA t (the z axis) for membership fraction $\lambda \in (0.1, 0.8)$ (the x axis) and policy variable $r \in (0.5, 0.95)$ with $\rho = 0.2$ and $\eta = 1.5$

by the same amount. Producers in the insider countries use a less carbon intensive process, and producers in outsider countries continue to use the original process (where one unit of production creates one unit of emissions). Because the outsiders produce less of the carbon intensive good, their emissions fall, leading to negative leakage. Consumption shifts from the insider countries to the outsider countries.

Figure 8 shows the two graphs of leakage (the z axis), with and without the BTA, as a function of membership $\lambda \in (0.1, 0.8)$ (the x axis) and the demand elasticity $\eta \in (0.5, 3)$ (the y axis); the top orthant ($z > 0$) shows leakage under free trade, and the bottom orthant ($z < 0$) shows leakage under the aggressive BTA. In both cases, it is less than 10% in absolute value over most of the parameter space shown in the figure.

In the symmetric case, where there is no trade prior to regulation, the aggressive BTA provides the outsiders with gains from trade and therefore increases their welfare. The BTA lowers insiders' welfare. If, initially, the outsiders exported the carbon intensive commodity (as is the case with China), then the BTA causes their terms of trade to deteriorate, lowering their welfare. In this case, the welfare effect of the BTA on insiders is ambiguous, depending on how close the BTA is to the optimum tariff.

A BTA that leads to zero leakage leaves the world price unchanged, thus leaving emissions in the unconstrained countries fixed at their BAU level. The ad valorem BTA that eliminates leakage is $s = \rho\frac{1-r}{(1-\rho+\eta)}$. This tax

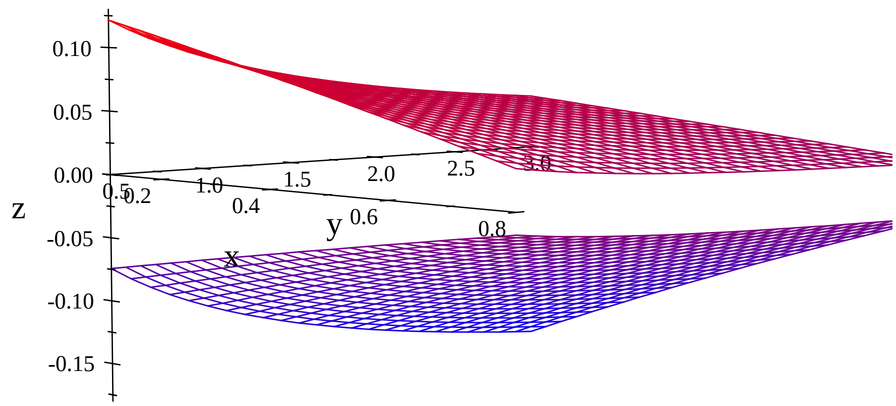

Figure 8: Leakage (the z axis) under the aggressive BTA (for $z < 0$) and under free trade (for $z > 0$) as function of $\lambda \in (0.1, 0.8)$ (the x axis) and $\eta \in (0.5, 3)$ (the y axis).

is independent of the membership ratio λ. If each of the "other insiders" uses a BTA that leaves their equilibrium excess demand unchanged relative to BAU, then the level of the BTA that a particular insider must choose to achieve the same goal, does not depend on how many other countries are insiders and how many are outsiders. Not surprisingly, the modest BTA that eliminates leakage is always less than the aggressive BTA given by equation (9). For example, for $\rho = 0.2$ and $\eta = 1.5$ and over the range of λ, r graphed in Figure 7, the modest ad valorem BTA is between 35% and 39% of the aggressive BTA. If $\eta = 0.8$, the modest BTA is between 50% and 55% of the aggressive BTA.

4 Literature Review

The possibility that reactions by non-regulating countries (the outsiders) can undermine the regulatory actions of a group of countries has been a prominent theme in environmental economics for decades (Hoel 1992). The 1999 Kyoto Protocol special issue of *Energy Journal* reviews the literature on carbon leakage. Tables 2 and 3 summarize nine recent papers on the subject; five use CGE models and four use partial equilibrium models. After discussing these I turn to an econometric study.

Mattoo et al. (2009) find that if by 2020 high income countries reduce carbon emissions by 17% relative to 2005 levels (equivalent to an estimated reduction of 28% relative to BAU) then low and middle income countries increase their emissions by 1%. They do not state these results in terms of the conventional definition of leakage. However, using the 2003 emissions levels reported in World Development Indicators 2007 (12,647 MMT CO2 in low and middle income countries and 12, 738 MMT CO2 in high income countries) these percent changes imply leakage of $\frac{(.01)12647}{(.28)12738} = .035$, or 3.5%. The authors argue that leakage is small because exports account for a small proportion of low and middle income country production of carbon intensive goods, and because the expansion in the export sectors draws resources out of less carbon intensive sectors, reducing production and emissions in those contracting sectors. The authors also estimate leakage in a simplified model which allows them to do Monte Carlo studies. In this exercise they fine average leakage of 11%; they offer hypotheses about why this simplified model leads to much larger leakage than the point estimate of their full model.

They find that the aggressive BTA based on the carbon content embodied in imports causes a significant decrease in exports from China and India and an increase in EU production, leading to negative leakage. This policy lowers developing country welfare, because it reduces the price that they receive for their exports. A symmetric BTA on imports and exports based on the carbon intensity of production in the high income (regulated) countries leads to zero leakage and a smaller loss in developing country welfare.

Fischer and Fox (2009b) and Fischer and Fox (2009a) use both a CGE and a partial equilibrium model to estimate leakage. The latter assumes that marginal production costs are an increasing function of abatement but are constant with respect to output, so supply elasticities are infinite. Home and foreign goods are differentiated, so that both are produced in equilibrium. They provide formulae for leakage under different policy scenarios. These formulae have the same flavor as those I provide above, but their constant marginal costs and differentiated products assumptions lead to important differences. Those assumptions enable the authors to use simulations from a CGE model to obtain parameter values needed to apply their formulae. (Most CGE models assume constant returns to scale and differentiated products, making it impractical to use these models to calibrate my formulae.)

For a scenario with a \$50/ton price on carbon emissions, their partial equilibrium estimates of leakage rates range from 60% in the oil and steel sectors to approximately 10% in the electricity sector and the paper, pulp, and print sector. The authors point out that much of this leakage is attributable to energy price changes and cannot be controlled by border adjustments or rebates. Because energy is a factor of production, the effect of its price change would be excluded from most partial equilibrium analyses. The authors therefore calculate "marginal leakage", defined as the change in the foreign sector's emissions induced by production price changes in that sector (rather than energy price changes). Their estimates of marginal leakage rates range from 57% for oil to 2% for the paper, pulp, and print sector. A BTA based on foreign emission intensity generates only an additional 8% reduction in net emissions relative to the carbon tax alone in the oil sector; the emissions reduction induced by the BTA is smaller for other sectors. (They do not provide the information that would enable the reader to easily convert the 8% reduction into a changed estimate of leakage.) Their CGE estimates of leakage are 28% for energy intensive manufacturing and 14% overall.

The contrast between Mattoo et al. (2009) and Fischer and Fox (2009a) is striking. The emissions reduction in the former paper is supported by a $241/ton carbon tax, and the tax in the latter is $50/ton. To the extent that leakage depends on the size of the emissions reduction in regulated countries, I would expect stricter regulation to increase leakage, but comparison of the papers shows the opposite, with a large difference in estimated levels of leakage. Of course, the two papers have important modeling differences, but they address the same policy question, and on that basis should be comparable.

Babiker (2005) argues that prior estimates of leakage are downwardly biased due to model assumptions that limit the ability of industries to relocate in response to environmental regulation. In his model, fossil fuels producers face decreasing returns to scale and perfect competition; electricity and non-energy intensive tradable goods are produced with CRTS technology by perfectly competitive firms. However, energy intensive tradable goods are produced under imperfect competition and with increasing returns to scale (IRTS). He estimates the leakage arising from emissions constraints in the OECD and the former Soviet Union consistent with the Kyoto Protocol, under several sets of assumptions about market structure. He finds a large shift in the energy-intensive industry out of the OECD. In that sector, the number of firms in the OECD (determined endogenously by a zero profits condition) falls by 2% and output per firm falls by 3.7% if domestic and foreign goods are differentiated, but if they are homogenous the number of firms falls by 53% and output per firm falls by 57%. The model produces leakage estimates ranging from 25% with IRTS and differentiated products, to 60% with CRTS and homogeneous products, to 130% with IRTS and homogenous products. The conclusion is that if IRTS and product homogeneity are accurate representations of energy intensive industries, at least in the long run, then unilateral climate policies may lead to higher global emissions.

Burniaux and Martins (forthcoming) describe the channels through which carbon leakage can occur. In the "energy markets channel", reduction in demand for carbon intensive fuels by countries with carbon prices causes a fall in the world price of such fuels. Lower fuel prices increase the quantity of fuel demanded in unregulated countries and can lead to an increase in global emissions. The structure of energy markets is important here; fuel markets must be integrated and fuel supply must be somewhat inelastic for leakage to occur through this channel. Changes in energy prices could also lead to negative leakage if emissions pricing in Annex 1 countries causes a fall in the price of oil relative to coal, which could lead to substitution away from coal and towards oil in countries such as China, which rely on coal for much of their energy needs. In the "non-energy markets channel", carbon emissions pricing leads to decreased domestic production of carbon intensive goods and substitution towards goods produced in unregulated countries. This shift in global production towards countries that do not have emissions pricing, and frequently have more carbon intensive methods of production, can result in increased global emissions. Capital may also relocate to the unregulated countries, again leading to an increase in global emissions.

To assess the importance of the different leakage channels, they conduct sensitivity analysis using a simplified two country, two good, three fuel (oil, coal, and low-carbon) framework, which was calibrated to mimic a larger CGE model. They seek to explain the 2% – 21% range of leakage estimates produced by a group of earlier models. They find that the "non-energy markets" channel has little impact on leakage, as leakage remains below 4% over the full range of parameters tested that affect this channel. They conclude that Armington substitution elasticities and the migration elasticity of capital are not key determinants of the magnitude of leakage. Assumptions regarding these parameters therefore do not cause the differences in leakage estimates across CGE models. In the "energy markets" channel, the key parameter is the supply elasticity of coal, with lower elasticities leading to higher levels of leakage. For elasticities between zero and two, the estimated leakage rate can exceed 20%. The value of this elasticity has not been precisely estimated, but over the range of values often used in the literature, the leakage rate is small.

McKibbin and Wilcoxen (2009) use a CGE model to estimate import tariffs that would result from border tax adjustments on imports into countries that have a carbon tax, from countries where carbon emissions are not priced. They also examine the extent to which leakage estimates depend on relative carbon intensities of production between importing and exporting countries. If the EU uses a carbon tax starting at \$20/ton and rising to \$40/ton over 40 years and also uses a BTA based on US carbon intensity, the effective tariffs are below 1% for tradable goods other than fuels. If the US uses this carbon tax and imposes a BTA based on China's carbon intensity, the effective tax rises to 4%. Absent a BTA, the EU carbon tax leads to 10% leakage; adding the BTA to the carbon tax leads to negative leakage. Absent a BTA, the US tax leads to 3% - 4% leakage; including the BTA again causes negative leakage. These results suggest that effective tariffs are small for most goods at moderate carbon tax levels (as in the partial equilibrium model in Section 3.2). In view of the small level of estimated leakage, the authors conclude that the modest environmental benefits of BTAs do not justify their efficiency cost and administrative complexity.

Demailly and Quirion (2008) use a partial equilibrium model to estimate the effect of EU carbon constraints on production and profitability in the EU iron and steel sector. The two-region model consists of EU15 and ROW, with the price of EU-produced iron and steel the same in the two regions. The EU carbon price is modeled as a gamma distributed random variable with mean price EUR20/ton CO_2 and variance of EUR40/ton. Producers undertake abatement until their marginal abatement cost equals the emissions price. They pass 75% of the cost increase on to domestic consumers, and 50% of the cost increase on to ROW consumers. (The authors do not explain why domestic and foreign prices of EU-produced steel are initially the same when the pass through rate differs.) The price of the ROW-produced product is assumed constant, thus eliminating an important channel of leakage.

At the expected price of carbon, the increased EU costs cause the domestic price to increases by 2.5%. Emissions in the covered sector fall by 12%, with an estimated leakage rate of 5% in their base case. The maximum range of leakage estimates across all combinations of parameter specifications considered in their sensitivity analysis is 0.5% to 25%, leading the authors to conclude that the iron and steel sector is not particularly vulnerable to leakage.

Ponssard and Walker (2008) use a partial equilibrium, oligopolistic competition model of the cement sector in a representative EU country with distinct coastal and inland markets to estimate the impact of carbon restrictions on production and profitability; they also estimate the leakage rate. There are N firms in regional markets, and each firm can operate several plants. Each plant's supply cost is determined as the sum of the marginal production cost multiplied by the quantity produced, and the transportation cost to each of the regional markets supplied by the plant. Plants are capacity constrained and, prior to the emissions policy, domestic coastal producers, domestic inland producers, and non-EU imports serve coastal markets; only domestic inland and coastal producers serve inland markets. The equilibrium in both markets is Nash-Cournot. The authors consider two scenarios for comparison: (i) the base case where coastal firms operate plants along the coasts only and inland firms operate plants inland only, and (ii) the general case where firms can operate plants in both regions of the country. The authors use data on production and trade of both cement and clinker to parameterize the model.

The base case leakage rate is 70% at an allowance price of EUR20/tonne CO2 and 73% at an allowance price of EUR50. These high estimates result partly from the low short run own price elasticity of demand they assumed (-0.27) and the exclusion of novel abatement technology, such as CCS, from the model. With a slightly higher elasticity of demand (-0.40), leakage is 56% at EUR20 and 67% at EUR50.

Ritz (2009), building on Fowlie (2009)'s study of a domestic market, considers an imperfectly competitive partial equilibrium model with a fixed number of regulated and unregulated firms selling a homogenous product. The equilibrium is Nash-Cournot. The regulated firms are able to switch to less carbon-intensive production methods, but the regulation increases their production costs and shifts production toward the unregulated firms. The author uses this model to estimate leakage when EU cold-rolled sheet steel producers face a price of carbon. In 2004 12 EU firms and 3 non-EU firms supplied steel to Europe. Assuming an elasticity of demand of 0.5, an initial operating profit margin of 20%, and an emissions intensity of production of 2tCO2 per ton of steel for both inside and outside firms, the author estimates that for linear demand leakage equals 9% when regulated firms make efficiency improvements and 75% in the absence of those improvements. The leakage rates are similar for constant-elasticity demand.

Aichele and Felbermayr (2010) is notable for its use of econometric methods to estimate leakage, and it shows the difficulty of this venture. (See also World Bank (2008).) Using panel data (15 sectors, 38 countries and 10 years), the authors regress net carbon imports for a country (or for an industry in the country) against variables commonly used in gravity models and the variable of interest, here a dummy to indicate whether the country signed the Kyoto Protocol. The use of the other control variables is an attempt to eliminate confounding effects, in order to be able to compare the effect of Kyoto Protocol membership on the behavior of a "typical country". Their estimates show that signing the Protocol is associated with an increase in carbon imports and a decrease in carbon production.

Econometric issues make it unclear whether they actually estimate a causal relation. I put aside those issues in order to discuss the manner in which they use their estimates to calculate leakage. Based on the coefficient of the participation dummy variable, they calculate that at the sample mean a signatory's imports of carbon exceeds that of a non-signatory by 3.07 mt; they ascribe a causal relation here, which I grant for the sake of discussing a more fundamental issue. They also calculate that average yearly growth rates in emissions are 0.33% lower for a signatory than a non-signatory, leading to an average difference in CO_2 production, between signatories and non-signatories, of 6.92 mt. They interpret this difference as the signatory's reduction due to having undertaken the Kyoto commitment, and they interpret the 3.07 mt as the increased emissions in non-signatories due to the signatory's increased imports. Based on this interpretation, their estimate of the leakage is $\frac{3.07}{6.92} = 0.44$, or 44%.

In order to see why this ratio cannot be construed as a measure of leakage, consider a case where all countries are ex ante homogenous and then randomly assigned to accept the Kyoto Protocol (the "treatment group") or to stay out of Kyoto (the "control group"). Econometric wizardry is unlikely to produce a cleaner experimental design than this one. We then observe that carbon imports of the treatment group are 3.07 mt higher than that of the control group, and carbon production of the former is 6.92 mt lower than that of the latter. This information tells us nothing about leakage. For example, the assumption that signing Kyoto causes the treatment group to reduce carbon production by 6.92 mt – an assumption the authors appear to make – implies that the carbon production in the control group is unchanged. (In that case, the signatories' 3.07 mt of increased imports must be offset by the non-signatories' decreased consumption). That assumption implies that leakage is zero, not 44%. Another interpretation consistent with these numbers is that Kyoto caused the signatories to decrease production by α and caused non-signatories to increase production by β, relative to the level that would have prevailed absent Kyoto, with $\alpha + \beta = 6.92$. In that case, leakage is $\frac{\beta}{\alpha}$, which can take any value.

An estimate of leakage requires an estimate of levels of carbon production if *no country* had signed the Protocol. Of course, if we had estimates of "but-for Kyoto carbon production levels" we could use those and the observed carbon production levels to calculate leakage, without detouring to consider changed imports.

Leakage can occur only if actions (e.g. those induced by Kyoto membership) in one country induce changes in other countries. When this relation exists, the outcomes (levels of carbon production) do not satisfy the "stable unit treatment value assumption" (SUTVA), needed in order to be able to ascribe, to the treatment, differences in outcomes between the treatment and the control groups. SUTVA states, in this context, that levels of carbon production in one country do not depend on whether another country has signed Kyoto. The researcher cannot have it both ways. It cannot be the case that trade creates a connection between actions in one country and outcomes in another country (e.g. increased emissions) and also true that SUTVA holds. This problem appears to be endemic to empirical studies on trade and the environment, not just the particular study under discussion here.

5 Discussion

Two kinds of questions arise at this point: How should economists use available evidence on carbon leakage to advise policy makers? How can economists improve the state of knowledge about the severity of carbon leakage?

Regarding the first question, there is a spectrum of possible recommendations that economists might make. At one end, we might tell policymakers that leakage is unlikely to create severe environmental or economic consequences (e.g. through the loss of domestic manufacturing) and that attempts to avoid leakage through BTAs are likely to create economic inefficiencies, administrative costs, and camouflage for protectionists; therefore, climate legislation should not include trade policies to counter leakage. At the other end of the spectrum, we might conclude that leakage is likely to be large and lead to large environmental and economic costs, and that BTAs are essential if we decide to pursue climate policy without near-global participation.

I take a middle view. It seems to me that we do not know much about the magnitude of leakage. My best guess is that leakage will be small or moderate, but I do not think that there is either the theoretical or empirical basis for asserting that with confidence. Amongst the non-economists who have even considered the question of leakage, there appears to be a widespread belief that it is important. Or perhaps people who are opposed to climate policy for other reasons appeal to leakage as a reason for inaction. In either case, I think that the danger of climate change is sufficiently great, and the risk to the trading system sufficiently small, that economists should concede the point: accept that non-global climate policy will be attended by BTAs, and concentrate on designing these so that they do little harm.

Regarding, the second question, I conclude that it would be particularly useful to have better estimates of parameters that can be used to calibrate *simple* models.

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Paper	Model	Key Assumptions	Emissions Policy	Leakage Policy	Estimated Leakage
Mattoo et. al., 2009	Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model: Dynamic CGE model calibrated to 2004 GTAP data, with 15 countries/regions, 21 sectors, and 6 types of electricity generation (coal, oil, gas, hydro, nuclear, other)	Production functions have constant elasticity of substitution; greater substitution across inputs in the long run than in the short run; demand allocated between domestic production and imports	17% reduction in emissions in high income countries relative to 2005 levels by 2020; no emissions reductions in low and middle income countries	None	Low and middle income country emissions increase by 1.0% relative to BAU, which implies a leakage rate of approximately 3.5%
	Stochastic approach: Latin Hypercube Sampling procedure over range of key parameter values plugged into reduced form model		28% reduction in Annex I country emissions relative to BAU by 2020 (or 17% reduction relative to 2005)	None	Mean "rate" of 11% with SD of 5%; 94% of sample between 0% and 20%
Burniaux and Oliveira Martins, 2010	Simplified static GE model (calibrated to GREEN) with two regions, multiple goods, three energy inputs (coal, oil, and carbon free)	Coal and oil tradeable, coal dfferentiated but oil homogeneous; carbon-free energy is non-tradeable; consumption good is differentiated by region of origin; production is specified by nested-constant elasticity of substitution functions	Kyoto Protocol	None	"If one assumes an elastic supply of coal, the leakage rates would tend to be small for a large configuration of other parameters' values." However, for coal supply elasticities <2, leakage >20%, and for elasticity=1, leakage can reach 40%.
Babiker, 2005	Static CGE model with seven regions, five energy goods, and two non-energy composites (energy-intensive and non-energy-intensive)	Various Armington assumptions; production either CRTS or IRTS	Kyoto Protocol	None	25%. --135%
Fischer and Fox, 2009 (Combining Rebates with Carbon Taxes)	Multisector, multiregion, static CGE model from GTAP	Standard Armington structure where elasticity of substitution between domestic and foreign composite is set to one half of that between foreign varieties (estimated econometrically)	\$50/ton C (approx equal to \$14/ton CO2) applied in the US to the six major energy-intensive sectors	None	14.2% overall, 12.8% for the covered sector, 27.4% for energy-intensive manufacturing
McKibbin and Wilcoxen, 2009	G-Cubed: Intertemporal GE model with 10 regions, divided into household, govt, and financial sectors, 12 industries, and a capital-goods producing sector; parameterized econometrically	Each industry modeled by stock market value maximizing representative producer facing exogenous prices; goods are differentiated by region, each region may import any good from any other region	\$20/ton C rising by \$0.50 each year up to \$40/ton C adopted in Europe	None	10% in 2010

Table 2: General equilibrium leakage estimates

Paper	Model	Key Assumptions	Emissions Policy	Leakage Policy	Estimated Leakage
Fischer and Fox, 2009 (BTAs vs Rebates)	Two country, two good, partial equilibrium model, parameterized using simulations from full blown CGE model		$50/ton C applied unilaterally in the US to certain carbon intensive industries	None	8% in electricity and 11% in paper and pulp, to 60% in iron and steel and 64% in oil; most of the leakage is due to energy price changes (3%, 2%, 14%, and 57% respectively are leakage rates attributable to production changes)
Ritz, 2009	Multi-country partial equilibrium model of steel industry, parameterized using estimates based on previous literature	Profit-maximizing firms produce a homogeneous good and face downward sloping demand; equilibrium is Cournot-Nash	EUR20/ton CO2 in EU	None	8.8-75.0% in cold-rolled sheet steel industry
Demailly and Quirion, 2008	Two region partial equilibrium model of iron and steel industry, parameterized using estimates from the literature	Profit-maximizing firms that equalize marginal abatement cost with emissions price; marginal cost increase pass through rate higher to domestic market than export market	EU ETS, under which the expected CO2 price is EUR20/ton CO2	None	5% in basic iron and steel industry in the central scenario; range of 0.5%-25% across range of parameters considered in sensitivity analysis
Ponssard and Walker, 2008	Partial equilibrium model of N firms in cement industry interacting in coastal and inland markets, calibrated to reference data	Markets characterized by oligopolistic competition and Cournot-Nash equilibrium; plants are capacity constrained	EU ETS, with emissions prices of EUR20 or EUR50/tonne CO2	None	70% at EUR20 and 73% at EUR50, decreasing with slightly higher price elasticity of demand to 56% at EUR20 and 67% at EUR50

Table 3: Partial equilibrium leakage estimates