

Competition in regional environmental policies when plant locations are endogenous¹

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Abstract

A two-region model is presented in which an imperfectly competitive firm produces a good with increasing returns at the plant level. Production of the good causes local pollution. The firm decides whether to maintain plants in both regions, serve both regions from a single plant or shut down. If the disutility of pollution is high enough, the two regions will compete by increasing their environmental taxes (standards) until the polluting firm is driven from the market. Alternatively, if the disutility from pollution is not as great, the regions will usually compete by undercutting each other's pollution tax rates.

Key words: Environmental policy; Tax competition; Plant location

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1. Introduction

There are at least two conceptually distinct types of environmental problems that can play a significant role in interregional and in international policy. One problem is transfrontier pollution such as acid rain, and global

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warming. Transfrontier pollution has attracted considerable attention, and a rapidly increasing amount of economic analysis.

A second and to some extent overlapping problem involves strictly *local pollution* externalities, but involves interregional and international considerations insofar as the location of production is endogenous. As environmental issues have moved to the forefront of public debate, regional politicians ambivalently worry that imposing stricter environmental standards will drive industry from their region, while strongly believing that highly polluting plants, although sometimes necessary, should only be located in someone else's region. These issues are now receiving considerable attention from an international perspective. The Canadian–U.S. Free Trade Agreement, the debate on North American free trade, and the completion of the internal market for the European Economic Community are forcing politicians to confront these issues. For example, some US and Canadian groups are worried that free trade will mean the movement of many of their plants to Mexico in order to take advantage of the cost savings afforded by lower environmental standards in Mexico.

Alternatively, if the disutility from pollution is sufficiently high, each region will want the polluting firm to produce only in the other region. In this case, the regions might bid up each other's environmental standards until the firm is driven from business. This can happen even though both regions would be better off if the firm operates a plant in one of the regions, and the region without the plant compensates the region with the plant for the pollution they experience. This is the case of NIMBY (Not in my back yard). For example, no one wants a hazardous waste site in their region, but we are collectively better off with one, than without one.²

In a previous paper (Markusen, Morey, Olewiler, 1993), henceforth MMO), we address the issue of plant endogeneity in a two-region model that involves two polluting firms choosing plant locations: location decisions that are influenced by the environmental policy of one region (the other region is passive). That model, which involves increasing returns to scale at the plant level, produces results that differ dramatically from those obtained from more traditional competitive models using Pigouvian marginal analysis.³ We show in MMO that regional welfare functions exhibit large discontinuities at critical levels of the environmental policy variables when plant location decisions are endogenous.

The purpose of the present paper is to turn our attention to the governments themselves, and consider the fact that the governments of two

² Mitchell and Carson (1986) consider the locating of such facilities in a model that emphasizes aversion to risk taking. There is no interregional competition in their model.

³ Examples of General equilibrium models with trade and pollution include Pethig (1976), Asako (1979), and Merrifield (1988). These models assume pure competition and constant returns to scale and thus are able to use marginal analysis. There is a literature on imperfect competition and pollution that examines policies, but does so in models without trade. Examples include Misiolek (1980) and Copeland (1991).

regions can compete in terms of their environmental policies. Our work builds on the literature on tax competition among governments. In the part of this literature most relevant to our work, capital and goods, but not individuals, are mobile across regions.⁴ In most of the tax competition literature, taxes are used to generate the revenues to provide public goods. Jurisdictions desire to attract industry and the resulting competition typically results in lower tax rates and the underprovision of public goods.⁵ See, for example, Arnott and Grieson (1981), Wilson (1985, 1986), Mintz and Tulkens (1986), Wildasin (1988, 1989), and several papers in a special issue of *Regional Science and Urban Economics* edited by Wildasin and Wilson (1991). These papers all model the 'rationale' which motivates destructive tax competitions. Mintz and Tulkens, in addition, explicitly consider the resulting non-cooperative equilibrium as the result of a game between the regions. Mintz and Tulkens use the Nash equilibrium concept with tax rates as the strategic variable.

There are a few papers that look specifically at environmental quality and government competition (Cumberland, 1979, 1981; Oates and Schwab, 1988). Both assume pure competition. Neither explicitly models the game between the governments. Cumberland considers environmental standards, rather than taxes, and argues that regions are likely to compete by relaxing standards to attract industry. He concludes that this competition will result in too low a level of environmental quality. He does not consider the NIMBY possibility. Oates and Schwab consider the joint determination of a tax rate on capital (to finance public goods), and the appropriate level of environmental quality. The n regions in their model do not compete directly in terms of either tax rates or environmental standards. Like the models cited above, the tax on capital is used to raise revenue and is distortionary. The nature of the *tax competition* in their model is a capital relocation externality; i.e. when capital is mobile, regions realize that as they level taxes to finance local public goods, capital will move to untaxed regions. The result is too few public goods and too low a level of environmental quality relative to a first-best optimum. Strategic behavior is not modelled.⁶

⁴ Along another vein, Tiebout (1956) generated a government competition literature where people are mobile and *vote with their feet*. In this literature, governments compete to provide a mix of public goods that maximizes households' utility. The resulting equilibria are efficient.

⁵ Because the focus of these articles is on the provision of public goods, and not negative externalities, a NIMBY case where tax rates are bid up cannot arise.

⁶ There are several recent papers examining strategic behavior among government regulators of pollution (See Hoel, 1991; Dockner and Long, 1991; Folmer et al., 1991). In each paper, government behavior is modeled as a cooperative or non-cooperative game when there is transboundary (global) pollution. Papers by Barrett (1994), Rauscher (1991), and Ulph (1992) consider other aspects of imperfect competition with non-cooperative government environmental policies. Barrett shows how strategic (rent shifting) motives influence policies, while Rauscher and Ulph focus on quantity standards versus pollution taxes. The potential impact of government decisions on industrial structure and plant location are not examined in any of these papers.

In this paper, we assume a single, imperfectly-competitive firm producing some product X with increasing returns to scale. The X firm may choose to build plants in both regions, a plant in only one of the regions, or not produce at all. The existence of shipping costs between regions is responsible for the fact that the firm may choose plants in both regions despite increasing returns to scale. Pollution is generated as a by-product of the production of X , but this pollution does not cross regional borders. There is also a competitive Y industry in each region. The Y industry does not pollute. The issue addressed is thus trans-border competition in environmental policies, not transfrontier pollution.

Each government's decision criteria is to maximize their region's consumer surplus from the consumption of X and Y , plus tax revenue, minus the region's disutility from pollution.⁷ These regional goals conflict. The resulting competition between the two governments is modelled as a two-stage non-cooperative game. In the first stage of the game, the two governments simultaneously set the values of environmental policy variables. These are interpreted as pollution taxes throughout the analysis, but they could also be thought of as regulatory variables that impact on the firm's marginal cost (e.g., requiring cleaner fuel or other more expensive inputs). In the second stage, the firm chooses one of four configurations of plants: a plant in both regions, referred to as (1,1), a single plant in Region A, denoted (1,0), a single plant in Region B, denoted (0,1), or zero plants, denoted (0,0). The game is solved backwards in the usual fashion. The second stage is solved first in two steps. We first solve for the firm's maximum profits given the levels of the pollution taxes and given a particular configuration of plants. We then solve for the firm's choice of plant locations given the tax levels. In the first stage of the game, we solve for the two governments' non-cooperative equilibrium levels of pollution taxes using a Nash (best response) solution concept.

The increasing-returns and discrete-choice aspects of the problem make it an interesting one, but unfortunately greatly add to its analytical complexity. In particular, the traditional reaction-curve analysis that allows the Nash equilibrium to be expressed as a fixed-point of some mapping is of little use here. There are large discontinuities in tax reaction curves as the firm changes the number/location of its plants, and the relationship between the discontinuities in the two countries is very sensitive to parameter values. The lack of continuity eventually led us to abandon the traditional ap-

⁷ For simplicity, we assume that the ownership of the firm is widely distributed throughout the 'world' so that the firm's profits are not taken into consideration in regional welfare. Because our industry is non-competitive, the optimal pollution tax is not equal solely to the marginal disutility from pollution, but is more complex as will be shown later in the paper. Thus, there may be tax revenue in excess of total pollution disutility.

proach. We are able to show the range of parameter values which support a particular equilibrium, and the critical combination of parameters that cause us to move from one equilibrium to another. But we resort to examples in order to illustrate the welfare losses from non-cooperative behavior, and do not attempt to provide an exhaustive characterization of all possible equilibria.

2. The effect of taxation on the number and location of plants

This section develops the model and solves for the equilibrium configuration of plants as a function of the two countries' tax rates. As noted earlier, the four possible equilibria are (1,1), (1,0), (0,1) and (0,0).

The two regions are assumed to be absolutely identical in all respects. The resulting symmetry aids us greatly in obtaining simple expressions for solutions. An individual consumer in each region has the utility function

$$U = \alpha C_x - (1/2)C_x^2 - \gamma(X_d + X_e) + C_y \quad (1)$$

where C_x and C_y are per capita consumption levels of X and Y respectively. $X = (X_d + X_e)$ is the total domestic production of X . X_d denotes production sold domestically and X_e denotes production that is exported. Assume one unit of pollution is produced in a region for each unit of X produced in that region. Thus γ is the marginal disutility of pollution to a consumer. Let N denote the total number of individuals in a region. Each individual views the total level of pollution in his or her region as exogenous, and in the absence of a pollution tax, or regulation, this externality will, *ceteris paribus*, lead to a market failure. Note that the system is also distorted by the market power of the X firm. To help simplify notation, we will normalize N at $N = 1$.

An individual is assumed to own L units of labor, and the production function for Y is simply $Y = L_y$, where L_y is the labor allocated to Y production out of the endowment of L units of labor. Y or L is numeraire (if the price of Y equals 1, then the price of L must equal one), and p_x denotes the price of X in terms of Y or L . There is no pollution associated with the production of Y . The X firm produces with a constant marginal cost m and with fixed costs as discussed below.

Let t denote the pollution tax levied on the production of X that is sold domestically, and let t_e denote the pollution tax that is levied on the production of X that is exported. The tax rate t_e can be thought of as the sum of the domestic pollution tax t plus a supplemental tax or subsidy, e , on export sales; i.e., $t_e = t + e$. Assume no other taxes. Allowing a region to differentiate between production for local consumption and exports gives each region greater flexibility, than would a single pollution tax, to address

jointly the pollution and market power distortions in a world where plant locations are endogenous.

Assume tax revenues are redistributed equally among all individuals. An individual's budget constraint is thus given by

$$L + tX_d + t_e X_e = p_x C_x + C_y \quad (2)$$

Maximizing (1) subject to (2) yields the very simple linear demand function

$$p_x = \alpha - C_x \quad (3)$$

Profits, before fixed costs, for the X producer from production for sale within a region ($C_x = X_d$) (recall N is normalized at $N = 1$) are given by

$$(\alpha - X_d)X_d - mX_d - tX_d \quad (4)$$

Since an increase in the marginal cost m is equivalent to a decrease in α in this formulation, we will simplify notation from here on by setting $m = 0$. Maximizing (4) with respect to X_d yields the firm's optimal supply.⁸

$$X_d = (\alpha - t)/2 \quad (5)$$

When the firm considers export sales, there is an equation similar to (4) but with t_e and an additional term for exporting costs: sX_e , where s is per-unit transportation cost. The supply function for exports (recall that populations are identical) is thus

$$X_e = (\alpha - s - t_e)/2 \quad (6)$$

Let $\pi(i, j)$ denote the profits of the firm in market structure $(i, j) \in \{1, 0\}$. Let subscripts a and b denote regions A and B respectively. Let G denote the plant-specific fixed cost and F the firm-specific fixed cost. Inserting (5) and (6) into the profit equations, the maximized values of profits under each market structure are given by

$$\pi(1, 1) = [(\alpha - t_a)^2 + (\alpha - t_b)^2]/4 - 2G - F \quad (7)$$

$$\pi(1, 0) = [(\alpha - t_a)^2 + (\alpha - s - t_{ae})^2]/4 - G - F \quad (8)$$

$$\pi(0, 1) = [(\alpha - s - t_{be})^2 + (\alpha - t_b)^2]/4 - G - F \quad (9)$$

and $\pi(0, 0) = 0$.

For a given set of tax rates, the firm will choose that configuration of plants that maximizes its profits. This configuration can be found by using equations (7)–(9) and $\pi(0, 0)$ to determine maximum profits, at the given tax rates, for each of the four possible configurations. Said loosely, the firm

⁸ We assume throughout (and specify in the examples) that L is sufficiently large such that consumers are able to pay for the X produced at the implied price. Resources used for fixed costs may come from the 'outside world'.

will choose the (1,1) configuration, rather than (1,0) or (0,1), when t_e and s are large (exports are less attractive as t_e and/or s increases); t is small (production for local consumption becomes less attractive as t increases); and G is small (a second plant becomes less attractive as G increases). The firm will choose not to operate, (0,0), given sufficiently large values of G and F . For example, (1,1) at $t = t_e = 0$ corresponds to a situation where plant-specific costs are low relative to the size of the market (α) and low relative to shipping costs (s) so that the X producer prefers to bear the fixed cost of an additional plant relative to the unit shipping cost. Horstmann and Markusen (1992) analyzes these determinants of market structure in more detail. Note that the firm's choice of plant locations does not directly depend on the disutility from pollution, γ (the demand price is independent of γ).

The next step is to determine each region's choice of tax rates. Before determining the non-cooperative equilibrium tax rates that will result when plant locations are endogenous across regions, we derive, as a pedagogic device to help determine the actual equilibrium, each region's optimal tax rates under the artificial assumption that plant locations are exogenous. These tax rates are set ignoring the strategic nature of the competition between the regions, and, since they are set to equate the marginal benefits and costs from pollution and market power, can be interpreted as the Pigouvian tax rates. They are therefore the optimal *non-strategic Pigouvian* tax rates. For brevity, we will refer to them as the *non-strategic* tax rates and identify them with the superscript η ; i.e. t^η and t_e^η .

3. Regional social welfare and optimal taxes for exogenous plant locations: The optimal non-strategic tax rates

Substituting equations (2) and (3) into (1) and multiplying by N (normalized to $N = 1$) gives social welfare for the region.

$$W = U = (1/2)C_x^2 + (t - \gamma)X_d + (t_e - \gamma)X_e + L \tag{10}$$

If one plant is operating in each region, (1,1), $C_x = X_d$ and $X_e = 0$ (if we let X_m equal imports of X , $X_m = 0$ as well). Welfare of each region is thus

$$W(1, 1) = (1/2)X_d^2 + (t - \gamma)X_d + L \tag{11}$$

Under asymmetric plant configurations, (1,0) or (0,1), Region A's welfare equations are

$$W_a(1, 0) = (1/2)X_d^2 + (t_a - \gamma)X_d + (t_{ae} - \gamma)X_e + L \tag{12}$$

$$W_a(0, 1) = (1/2)X_m^2 + L \tag{13}$$

where X_m is equal to the exports of Region B.

Now consider the optimal taxes for a region *assuming* exogenous plant locations. Begin by considering the plant configuration (1, 1). To obtain the non-strategic pollution tax for a (1, 1) market structure differentiate (11) with respect to t and set the derivative equal to zero.

$$\frac{dW(1, 1)}{dt} = (X_d + t - \gamma) \frac{dX_d}{dt} + X_d = 0 \quad \frac{dX_d}{dt} = -\frac{1}{2} \quad (14)$$

where the second equation is derived from (5). Substituting the second equation of (14) into the first and using (5), we get the non-strategic tax formula

$$t^n = \alpha/3 + 2\gamma/3 \quad (15)$$

Substituting (15) into (5), we get X^n and substituting X^n and t^n into (11), we get welfare under the (1, 1) market structure, denoted W^n .

$$X^n = (\alpha - \gamma)/3 \quad (16)$$

$$W^n(1, 1) = (\alpha - \gamma)^2/6 + L \quad (17)$$

Next, consider the taxes that the government of Region A will set on pollution associated with production for domestic consumption and for export, given the exogenous configuration of plants (1, 0). Assume that the firm is able to price discriminate between the regional markets (prices can be set independently in A and B). Referring to welfare in Eq. (12), we see that the derivative with respect to t is the same as (14), and so Region A will set $t = t^n$ as in the case of market structure (1, 1). To determine t_e^n , differentiate (12) with respect to t_{ae} to obtain

$$\frac{dW_a(1, 0)}{dt_{ae}} = (t_{ae} - \gamma) \frac{dX_e}{dt_e} + X_e = 0 \quad \frac{dX_e}{dt_{ae}} = -\frac{1}{2} \quad (18)$$

where the second equation follows from (6). Substituting the second equation of (18) into the first and using (6), we get the non-strategic export tax formula

$$t_e^n = (\alpha - s + \gamma)/2 \quad \text{where} \quad (t_e^n - \gamma) = (\alpha - s - \gamma)/2 \quad (19)$$

Therefore, each region will set $t = t^n$ and $t_e = t_e^n$ if they ignore the strategic interactions. Substituting (19) into (6) we get the non-strategic export function

$$X_e^n = (\alpha - s - \gamma)/4 \quad \text{where} \quad (t_e^n - \gamma)X_e^n = (\alpha - s - \gamma)^2/8 \quad (20)$$

For the remainder of the paper, we will assume parameterizations of the model such that $(\alpha - s - \gamma)$ is positive. Elaborating, $(\alpha - s - \gamma) > 0$ implies that pollution is not so bad that the export tax is prohibitive (of course, fixed costs may imply negative profits such that the firm does not enter); if the

firm does choose to export, the tax revenues from exports minus the disutility from pollution on those exports, $(t_e^n - \gamma)X_e^n$, is positive.

To get social welfare for Region A with plant configuration (1, 0) at tax rates (t^n, t_e^n) , equation (12) indicates that we simply add the right-hand equation of (20) to (17).

$$W_a^n(1, 0) = (\alpha - \gamma)^2/6 + (\alpha - s - \gamma)^2/8 + L > W^n(1, 1) \tag{21}$$

Equation (21) and its right-hand inequality indicate that, if the firm chooses only a single plant at the non-strategic tax rates, the region that gets the plant is better off than if the firm chooses two-plants. When Region A gets the sole plant at (t^n, t_e^n) , it realizes the same welfare benefit from domestic sales that it does in the (1, 1) configuration, but, in addition, it captures the benefit of tax revenue in excess of the disutility of pollution on export sales.

If there is just one plant, the region which does not get the plant realizes the welfare level shown in Eq. (13), where $X_{bm} = X_{ae}$. Region B's welfare in (1, 0) at (t^n, t_e^n) is

$$W_b^n(1, 0) = (\alpha - s - \gamma)^2/32 + L < W^n(1, 1) < W_a^n(1, 0) \tag{22}$$

Thus if plant configuration (1, 0) or (0, 1) is chosen by the X producer at (t^n, t_e^n) , the region that does not get the plant does worse than the region that does, and worse than in market structure (1, 1). The country without the plant receives no tax revenue net of pollution disutility, and receives a lower consumer surplus from X due to the higher price caused by the transport cost.

A final point to note is that we can substitute the formulae for t^n and t_e^n in (15) and (19) respectively into the profit functions (7) and (8). Some manipulation will yield the result that

$$\pi^n(1, 1) - \pi^n(1, 0) = (\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/16 - G \tag{23}$$

It is clear that, for given values of α , s , and γ (subject to our earlier restriction that $(\alpha - s - \gamma) > 0$), *there necessarily exist values of G such that the case in which one plant is chosen and the case in which two plants are chosen at the non-strategic tax rates both occur*. As we increase G beginning at $G = 0$, two plants are chosen, then (23) equals zero at some value of $G > 0$ (the firm is indifferent between one and two plants), and one plant is chosen for still higher values of G .

4. Non-cooperative environmental policy equilibria: Three cases

Depending on the values of the parameters, a number of different types of non-cooperative equilibria can occur.

4.1. Case I: More plants, too much pollution

For Case I, initially assume the firm will choose one plant at $t^n = t_a = t_b$, $t_e^n = t_{ae} = t_{be}$. Said loosely, Case I assumes that pollution is not ‘too bad’ and that plant-specific cost (G) is large relative to the shipping cost s .

Let $\pi^n(1, 0)$ denote the profits of the X producer when it locates its single plant in Region A, given that A maintains its non-strategic tax rates. In terms of this notation, the initial assumption of Case I is that $\pi^n(1, 0) > 0$ ((8) is positive at (t^n, t_e^n)), and

$$\pi^n(1, 0) > \pi^n(1, 1) \quad \text{implying} \quad (\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/16 - G < 0$$

where the second inequality follows from (23).

If both countries impose taxes of t^n and t_e^n , the firm will service one region by exports. Assume without loss of generality that the firm produces for both regions from a single plant in Region A. Region A earns the welfare level given in equation (21) and Region B earns the welfare level given in Eq. (22). Region A’s welfare is significantly higher than Region B’s. This situation cannot be a Nash equilibrium of our simple game. Region B can under-cut Region A’s tax schedule by an arbitrarily small amount, and given these new rates, the X producer will switch to Region B. Equations (12), (13), (15) and (19) can be used to demonstrate that Region B has improved its welfare by this small tax under-cutting. Thus (1, 0) with tax schedule (t^n, t_e^n) cannot be an equilibrium.

Proposition 1. If one plant is chosen at t^n, t_e^n , this situation cannot be a Nash equilibrium because there is an incentive for the region without the plant to undercut.

The under-cutting process must continue over some finite interval. The under-cutting process may be terminated either by the governments, or by the firm switching to two plants. Referring to equations (12) and (13), the welfare of the region with the plant must decrease (as taxes deviate more from their non-strategic levels) and the welfare of the region without the plant must increase (its consumer surplus must increase as its import price

falls with the fall in the other region's export tax) as the under-cutting continues.

Eventually we may have an equilibrium at a (t, t_e) combination with plant locations $(1, 0)$ or $(0, 1)$ if (12) equals (13), and if it continues to be the case that $\pi(1, 0)$ or $\pi(0, 1)$ exceeds $\pi(1, 1)$. We will not develop this possibility in detail, but instead concentrate on the case when, as the under-cutting proceeds, we arrive at (t, t_e) values such that $\pi(1, 0)$ or $\pi(0, 1) < \pi(1, 1)$ and the firm switches to one plant in each country.

Note that there is a discrete change in a region's incentive to under-cut when taxes fall to the level that supports two plants. Above these tax rates, a region is engaged in under-cutting to move itself away from the situation of having no plant, importing at high cost and receiving no tax revenue. When the taxes fall to the critical levels necessary to support $(1, 1)$, each country has one plant and further under-cutting would be for the purpose of gaining the additional tax revenue from export sales, but at the expense of higher pollution levels.

We propose the following as a possible equilibrium. Under-cutting occurs until each region's export tax reaches the level $t_e^\epsilon = \gamma$, such that each region is indifferent to having production for export. Second, each region's domestic tax is cut until the X producer is just indifferent to maintaining two plants and switches to $(1, 1)$. This tax rate, which we will denote by t^ϵ is found by setting equation (7) equal to (8), letting $t_e = \gamma$ and solving.

$$t^\epsilon \equiv \alpha - ((\alpha - s - \gamma)^2 + 4G)^{1/2} \tag{24}$$

Several things can be deduced at this proposed equilibrium. First, neither region has an incentive to lower its export tax further to induce the firm to shut its other plant because the added pollution will outweigh the tax revenue. Second, neither region has an incentive to raise its export tax since this has no effect (there are no exports in $(1, 1)$). Third, neither region has an incentive to lower its domestic tax because this is already below t^n : if the firm chooses one plant at (t^n, t_e^n) and then the export taxes are lowered, it must be the case that the domestic taxes are then lowered to induce the firm to maintain two plants. Fourth, profits of the X producer are clearly positive at the proposed equilibrium and the producer is willing to maintain two plants by definition of t^ϵ .

Two additional conditions must be established to prove that there is non-cooperative equilibrium at $(t^\epsilon, t_e^\epsilon)$. At the proposed equilibrium, neither region must have an incentive to raise its domestic tax to drive the plant out. Let $W^\epsilon(1, 1)$ be the welfare level a country enjoys when $t = t^\epsilon, t_e = t_e^\epsilon$. Let $W_a^\epsilon(0, 1)$ be the welfare enjoyed by Region A if A then raised taxes to drive out the local plant, B's taxes remaining constant. $W_b^\epsilon(1, 0)$ is similarly

defined. The necessary condition for the region with a plant not to want to shed its plant is that $W^\epsilon(1, 1) > W_a^\epsilon(0, 1) = W_b^\epsilon(1, 0)$. A sufficient condition for this is that $t^\epsilon \geq \gamma$.⁹

Sufficient conditions for a (1, 1) equilibrium at $(t^\epsilon, t_e^\epsilon)$ are thus summarized as follows where the superscript ϵ denotes the non-cooperative equilibrium tax rates.

Proposition 2. If one is plant chosen at (t^η, t_e^η) and if $t^\epsilon \geq \gamma$, market structure (1, 1) is a non-cooperative equilibrium with tax rates $t_a^\epsilon = t_b^\epsilon = t^\epsilon$ (defined in (24)), $t_{ac}^\epsilon = t_{bc}^\epsilon = \gamma$.

It is easy to find parameterizations of the model such that the conditions of Proposition 2 hold, and thus (1, 1) is an equilibrium market structure at $t = t^\epsilon$ (given by (24)), and $t_e = t_e^\epsilon = \gamma$. Table 1 gives such a parameterization and associated results (indeed, $t^\epsilon < \gamma$ in Table 1, emphasizing that $t^\epsilon \geq \gamma$ is sufficient but not necessary).

Result 1 in Table 1 indicates that t^η and t_e^η can significantly exceed t^ϵ and t_e^ϵ . The direct profit calculating in Result 2 indicates that the firm will operate only one plant at (t^η, t_e^η) . Result 3 indicates that the example satisfies the welfare condition of Proposition 2, implying that at (1, 1) with tax rates $(t^\epsilon, t_e^\epsilon)$, neither region can do better by raising its tax sufficiently to drive out the plant and import instead. Result 4 implies that neither country can do better by lowering its export tax to induce the firm to shut its other plant: the additional tax is outweighed by the disutility of additional pollution. Thus the two countries have no incentive to deviate from tax rates $(t^\epsilon, t_e^\epsilon)$. Result 5 of Table 1 indicates that the firm also has no incentive to deviate from two plants. Thus (1, 1) is a Nash equilibrium.

Table 1 then presents some welfare effects. Welfare for each region is presented under the arbitrary assumption that the one plant is in Region A, (1, 0), rather than (0, 1) at tax rates (t^η, t_e^η) . Equivalent figures for the (0, 1) market structure are found by simply reordering the two regions. The welfare numbers at the bottom of Table 1 indicate that the combined welfare level of the two regions is 4.4% higher with (1, 0) than with (1, 1) (the two identical utility functions are additive). But the higher aggregate welfare with (1, 0) is very unevenly distributed. Region A gets both the tax

⁹ If $t^\epsilon \geq \gamma$, the country loses the non-negative excess of tax revenue over the disutility of pollution plus loses consumer surplus from the higher import price if it drives the plant out.

The last condition is more subtle. Each country must not have an incentive to induce the X producer to close its foreign plant through some combined policy of raising its domestic pollution tax above t^ϵ (where $t^\epsilon < t^\eta$), compensated for by a sufficient lowering of its export tax below t_e^ϵ . We can show that this last condition need not be specified as an additional assumption (i.e., it is implied by the other assumptions). This is demonstrated in a short appendix to the paper.

Table 1
One plant chosen at the non-strategic tax rates

A numerical example of a non-cooperative equilibrium with plant locations (1, 1) at $t_a^\epsilon = t_b^\epsilon = t^\epsilon \equiv \alpha - ((\alpha - s - \gamma)^2 + 4G)^{1/2} < t^n$, $t_{ae}^\epsilon = t_{be}^\epsilon = \gamma < t_c^\epsilon$

Parameterization

- $s = \gamma = 1$, $\alpha = 8$, $G = 3.6$, $F = 4$, $L = 16$
 These parameter values imply the following results:
 (1) $t^\epsilon = 0.901 < t^n = 3.33$, $t_c^\epsilon = 1 < t_e^\epsilon = 4.0$
 (2) $\pi^n(1, 1) = -0.296 < \pi^n(1, 0) = \pi^n(0, 1) = 0.102$
 (3) $W^e(1, 1) = 21.947 > W_a^e(0, 1) = W_b^e(1, 0) = 20.500$
 (4) $(t_c^\epsilon - \gamma) = 0$
 (5) $\pi^\epsilon(1, 1) = \pi^\epsilon(0, 1) = \pi^\epsilon(1, 0) = 14.000 > 0$

Welfare implications

	At the non-strategic tax rates (1, 0) at (t^n, t_c^ϵ)	The non-cooperative equilibrium (1, 1) at $(t^\epsilon, t_c^\epsilon)$
Market structure and taxes		
Welfare of Region A	28.712	21.947
Welfare of Region B	17.125	21.947
Sum of A and B	45.837	43.894
X producer's profits	0.102	14.000
Total pollution	3.835	7.099

revenue in excess of pollution disutility $((t^n - \gamma) > 0)$ and the consumer surplus gain from a lower price for X. Thus Region B has an incentive to under-cut Region A's taxes. The result, for the parameterization of Table 1, is a Nash equilibrium (1, 1) at $(t^\epsilon, t_c^\epsilon)$ with Region A doing worse and Region B doing better than at (1, 0).¹⁰

We emphasize that the non-strategic tax rates are not in general a Pareto optimum for the two regions, nor is the number of plants in this outcome necessarily optimal. In the example of Table 1, the two regions can cooperatively achieve a Pareto improvement over the non-strategic outcome in one of two ways: (1) both regions can agree to set prohibitive export taxes and set their domestic taxes as close as possible to (or at) t^n subject to the firm breaking even with two plants, or (2) Region A can set $t = t^n$ and lower its export tax below t_c^ϵ to take into account the consumer surplus generated in B by its export to B, plus A makes a transfer payment to B. The first option (giving two plants) is better given the parameterization of Table 1, but higher plant-specific fixed costs make the one-plant option preferred.

Finally, we emphasize that such an outcome is much more general than

¹⁰ Note that there is no suggestion that this is a unique Nash equilibrium given the assumptions of Proposition 2.

this simple example suggests. To recap, the equilibrium illustrated by the example in Table 1 occurs whenever (23) and (8) are both positive (one plant is chosen at the non-strategic tax rates), and (24) exceeds γ (regions do not have the incentive to force the plant out at (t^e, t_e^e)). These restrictions are mutually consistent for a wide range of parameter values, roughly speaking situations in which G is relatively large and γ is relatively small.

4.2. Case II: Correct number of plants, too much pollution

In this section, we assume that the X producer will choose two plants at tax rates (t^n, t_e^n) . Specifically, and with reference to equation (23), parameters are chosen such that

$$(\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/16 - G > 0 \quad (25)$$

We can move from Case I to Case II simply by lowering G (plant scale economies become less important), and indeed that is what we will do in the numerical example of Table 2.

The fact that in Case II the firm chooses two plants at the non-strategic tax rates does not imply that $(1, 1)$ is an equilibrium at (t^n, t_e^n) . One region may wish to under-cut on its export tax to induce the firm to shut its foreign plant, if the resulting increase in tax revenue exceeds the added disutility of pollution. Note that in an initial configuration of $(1, 1)$, neither region has an incentive to cut its domestic tax below t^n , since that will have no effect on the firm's location decisions. Also note that by inequality (22), neither region has an incentive to raise its domestic tax to induce the firm to shut its local plant.

Thus to determine whether there is a noncooperative $(1, 1)$ equilibrium at (t^n, t_e^n) we need only examine a region's incentives to cut its export tax below t_e^n . To determine this, set $t_a = t_b = t^n$ and solve for the value of t_{ae} that makes the firm indifferent between $(1, 1)$ and $(1, 0)$; specifically, substitute t^n from equation (15) into (7) and (8) for t_a and t_b , and set (7) equal to (8). Rearranging one obtains

$$(\alpha - s - t_{ae})^2/4 = (\alpha - \gamma)^2/9 - G \quad (26)$$

Region A has an incentive to deviate to this lower export tax t_{ae} if and only if $t_{ae} > \gamma$ (tax revenue per unit of export production exceeds the disutility of pollution). Substitute γ for t_{ae} in equation (26). The value of t_{ae} that solves (26) will exceed γ if and only if

$$(\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/4 - G < 0 \quad (27)$$

If the inequalities in (25) and (27) both hold (and $\pi(1, 1) > 0$), then two plants will be chosen at the non-strategic tax rates, but these tax rates

cannot be an equilibrium. Each region has an incentive to deviate by cutting its export tax. *It should be clear that values of G must exist such that both the inequalities (25) and (27) hold simultaneously.*

Proposition 3. If G is chosen such that (25) and (27) both hold at (t^n, t_e^n) , two plants are chosen, but the non-strategic tax rates cannot be an equilibrium.

Assume that (25) and (27) both hold. Suppose A begins the process by deviating to the value of t_{ae} given in (26). The firm shuts its plant in B and supplies both regions from its plant in A. B initially enjoys a lower level of consumer surplus because its price for X is higher and B loses its tax revenue $(t^n - \gamma)X^n$.¹¹

Region B should now cut its domestic tax by a small bit to regain a plant to supply for domestic consumption. The added consumers' surplus and tax revenues will more than offset the disutility from the resulting pollution. Region B should in turn cut its export tax to capture A's market, provided $(t_{be} - \gamma)$ remains positive. The under-cutting continues in this manner, with each region in turn cutting its domestic tax and cutting its export tax to capture the foreign market. This process comes to an end when there is no incentive to capture the other region's market; i.e., when there is no longer an incentive to get the firm to shut its foreign plant. This occurs when the export tax is driven down to $t_e = \gamma$. Given this export tax, a country sets its domestic tax as high as possible without losing its domestic market. Thus its domestic tax t^e is given by the same formula (although it does not have the same value) given in (24).

Proposition 4. If two plants are chosen at (t^n, t_e^n) ((25) holds), and if (27) holds as well, a non-cooperative equilibrium configuration of plants is (1, 1) with both countries having domestic taxes of $t_a = t_b = t^e$ (defined in (24)) and export taxes of $t_e^e = \gamma$.

Table 2 presents an equilibrium in which the configuration of plants is (1, 1) at the nonstrategic tax rates, but in which tax competition drives the two regions' tax rates down below t^n , to the rates indicated in Proposition 4. The parameterization differs from that of Table 1 only in that G is lowered to 3.0. Result 1 of Table 2 indicates that the parameters satisfy both the inequalities (25) and (27), so that two plants are chosen but that each country

¹¹ It can be shown using (26) that $t_{ae} > t^n - s$. Because switching to one plant saves the firm the fixed cost G , Region A does not have to cut its export tax so far that the export tax in A is less than the domestic tax in B by the amount of the transport cost. Thus when the firm switches to one plant in A, the price of X in B rises.

Table 2

Two plants chosen at the non-strategic tax rates

A numerical example of a non-cooperative equilibrium with the configuration of plants (1, 1) at $t_a^e = t_b^e = t^e \equiv \alpha - ((\alpha - s - \gamma)^2 + 4G)^{1/2} < t^n$, $t_{ae}^e = t_{bc}^e = \gamma < t_c^n$

Parameterization

$s = \gamma = 1$, $\alpha = 8$, $G = 3$, $F = 4$, $L = 16$

These parameter values imply the following results:

- (1) $(\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/16 - G = 0.194 > 0$
 $(\alpha - \gamma)^2/9 - (\alpha - s - \gamma)^2/4 - G = -6.56 < 0$
- (2) $t^e = 1.07 < t^n = 3.33$, $t_c^e = 1 < t_c^n = 4.0$
- (3) $\pi^n(1, 1) = 0.904 > \pi^n(1, 0) = 0.702$
- (4) $W^n(1, 1) = 24.165 > W^n(1, 0) = 22.077$
- (5) $(t^e - \gamma) = 0.07 > 0$, $(t_c^e - \gamma) = 0$
- (6) $\pi^e(1, 1) = \pi^e(0, 1) = \pi^e(1, 0) = 14.0 > 0$

Welfare implications

	At the non-strategic tax rates ^a	The non-cooperative equilibrium
Market structure and taxes	(1, 1) at (t^n, t_c^n)	(1, 1) at (t^e, t_c^e)
Welfare of Region A	24.165	22.077
Welfare of Region B	24.165	22.077
Sum of A and B	48.330	44.154
X producer's profits	0.904	14.000
Total pollution	4.670	6.926

^aNote that this is also a Pareto Optimal outcome; i.e. $t^* = t^n$ and $t_c^* = t_c^n$.

has an incentive to deviate from (t^n, t_c^n) by lowering its export tax to induce the firm to shut its foreign plant. Result 2 states that the Nash equilibrium tax rates are $t^e = 1.07$ and $t_c^e = 1.0$. Result 3 verifies that the firm earns higher profits as a consequence of choosing two plants at the non-cooperative tax rates, while Result 4 verifies that the two regions lose as a result of this competition. Result 5 notes that each region earns a surplus of tax revenue over the disutility of pollution on production for domestic consumption at the Nash equilibrium, and verifies that export taxes are set such that there is no equivalent surplus on (potential) exports, so that neither region has an incentive to under-cut. Result 6 of Table 2 notes that the firm is indifferent between one and two plants at the non-cooperative equilibrium.

The welfare implications of noncooperative equilibrium are summarized relative to the (1, 1) configuration of plants with tax rates t^n . This is done at the bottom of Table 2. Tax competition reduces the welfare of the two regions by almost 10% and significantly increases the profits of the firm. Total pollution is 48% higher at the Nash equilibrium than with non-strategic taxes. It should also be noted that the non-strategic tax rates are Pareto optimal in this case (they maximize the sum of Region A and Region

B's welfare).¹² Note that, unlike in Case I, neither region has to make a side-payment to maintain this Pareto Optimal cooperative equilibrium, each just needs to agree to impose the non-strategic tax rates.

Note that there is a certain continuity between Cases I and II. We move between the cases simply by lowering G , and therefore plant scale economies, making two plants more attractive. We could also move from Case I to Case II by lowering γ , which would lower the non-strategic tax rates, effectively making the market bigger and encouraging the firm to choose the high fixed-cost option of two plants. The *formulae* for the non-cooperative tax rates are also the same in the two cases: the export tax is set at the disutility of pollution and the domestic tax is then raised as far as possible such that the firm does not close the local plant. But the *value* of the non-cooperative domestic tax is different in the two cases, since the values of the parameters are necessarily different.

As was true with Case I, the outcome in Case II is supported by a much greater range of parameter values than is obvious from the numerical example of Table 2. The inequalities in Result 1 of Table 2 (plus the restriction that $\pi^7(1, 1) > 0$), hold for a wide range of 'intermediate' values for G . Much lower values of G support $(1, 1)$ at the non-strategic tax rates, but a region would have to cut its export tax so much to induce the firm to shut its other plant, that it is not worthwhile to do so. In this case ((25) holds but (27) does not), the non-strategic rates are Nash equilibrium rates.

4.3. Case III: Too few plants, too little pollution

Our third and final case focusses on the NIMBY possibility, in which neither region will accept a plant in a non-cooperative equilibrium but in which a cooperative equilibrium, with one plant, can achieve a higher level of joint welfare. In this situation pollution is sufficiently high, and plant-specific fixed costs are sufficiently high, that neither region wants a plant in

¹² This last point notwithstanding, note in Tables 1 and 2 that the sum of welfare (which is defined exclusive of the X producer's profits) and profits is larger at the Nash equilibrium than at $t = t^7$. The reason is that, from a 'world' point of view, the two regions are over-taxing the firm by ignoring the contribution of its profits to welfare. If each region took profits into account, tax rates would be substantially lower and could possibly be negative. The equilibrium tax rates would still be driven down by the existence of tax competition. The incentive to gain tax revenue by inducing the firm to shut its foreign plant still exists. Furthermore, equilibrium tax rates may remain too high from the 'world' point of view. For example, if each region held 50% equity in the firm, an action by Region A that reduces the profits of the firm by \$1 only reduces the equity income of Region A by \$0.50 (instead of \$0.00 in our formulation) so the tendency to over tax persists. This result is analogous to those derived in the tax competition literature without trade. See, for example, Mintz and Tulkens (1986), Oates and Schwab (1988) and Wildasin (1988, 1989).

their region, but pollution is not so bad that it is collectively best that X is not produced.

Suppose that we raise the plant-specific costs and the disutility of pollution sufficiently (relative to their levels in the two previous sections) such that the firm chooses only one plant at zero taxes and indeed loses money with two plants at zero taxes. In order to provide a straightforward illustration of NIMBY, we will in fact choose parameters such that the firm just breaks even with one plant if the country with the plant sets its export tax at the disutility of pollution, γ , and sets its domestic tax at zero: $t = 0$, $t_e = \gamma$.

Under these assumptions, one plant is chosen if both countries set their taxes at $t = 0$, and $t_e = \gamma$, so let us propose this as an equilibrium. With $t = 0$ and $t_e = \gamma$, equations (12) and (13) give us the welfare expressions for Regions A and B, assuming arbitrarily that A gets the plant.

$$W_a(1, 0) = (1/2)X_d^2 - \gamma X_d + L \quad W_b(1, 0) = (1/2)X_e^2 + L \quad (t_e = \gamma) \quad (28)$$

$(1, 0)$ cannot be an equilibrium at these taxes if $W_a(1, 0)$ is greater than or less than $W_b(1, 0)$. If $W_a > W_b$, then B will have an incentive to lower its domestic tax by a small amount to attract the plant, and under-cutting proceeds until the welfare in the region with the plant and the region without the plant are equal. The equilibrium will entail positive production.

NIMBY may arise when $W_a(1, 0) < W_b(1, 0)$ at these taxes. In that case, Region A has an incentive to deviate by raising its domestic and/or export taxes to drive the plant to B. Thus the proposed outcome cannot be a Nash equilibrium. Suppose A raises its taxes and drives the plant to B. B knows that if it raises its taxes, the plant will now be driven out completely since it cannot profitably return to A. NIMBY is thus the equilibrium if B would rather not have X produced at all than have it produced domestically at $t = 0$, and $t_e = \gamma$ (note that the appendix demonstrates that a region cannot do better than this by raising its domestic tax and lowering its export tax such that the firm's profits remain zero). With reference to (28), and recalling that $X = \alpha/2$ from (5) at $t = 0$, NIMBY then occurs when the sum of the first two terms of (28) are negative at $t = 0$ and $t_e = \gamma$ ($t_e - \gamma = 0$).

$$\alpha^2/8 - \gamma\alpha/2 = \alpha/2(\alpha/4 - \gamma) < 0 \quad (29)$$

Proposition 5. Choose G such that the firm just breaks even with one plant at $t = 0$, $t_e = \gamma$. Then $(0, 0)$ is a non-cooperative equilibrium if $\alpha/4 < \gamma$.

Table 3 presents an example in which the non-cooperative equilibrium is $(0, 0)$ but in which it is also true that the sum of the welfare levels in the two regions is higher if one of the regions will accept a plant at taxes $t = 0$, $t_e = \gamma$ (these taxes are not Pareto optimal: joint welfare could be further improved

Table 3

A numerical example of an non-cooperative equilibrium with no plants, (0, 0)

Parameterization $s = 1$, $\alpha = 8$, $\gamma = 2.1$, $G = 18.0025$, $F = 4$, $L = 16$

These parameter values imply the following results:

- (1) $X = 4.0$, $X_c = 2.45$, at $t = 0, t_c = \gamma$
- (2) $\pi(1, 0) = \pi(0, 1) = 0$ at $t = 0, t_c = \gamma$
- (3) $\pi(1, 1) < 0$ at all non-negative tax rates ($\pi(1, 1) = -11.75$ at $t = t_c = 0$)
- (4) $\alpha/4 = 2 < \gamma = 2.1$

Welfare implications

	Pareto-preferred outcome	The non-cooperative equilibrium
Market structure and taxes	(1, 0) at ($t = 0, t_c = \gamma$)	(0, 0) at ($t^* > 0, t_c^* > \gamma$)
Welfare of Region A	15.600	16.000
Welfare of Region B	19.001	16.000
Sum of A and B	34.601	32.000
X producer's profits	0.000	0.000
Total pollution	6.450	0.000

with a lower export tax and higher domestic tax). This case is quite the opposite of Case I. As in Case I, a transfer payment is needed to achieve a Pareto preferred outcome, but the direction of the transfer is now opposite to that of Case I. Here it is the region *without* the plant that must pay the region with the plant to achieve the cooperative outcome. We also have the opposite results to Case I with respect to both the numbers of plants and the level of pollution. Here we have two few plants and too little pollution at the Nash equilibrium.

To recap the relationship among our three cases, consider beginning with a parameter that supports Case II. We move to Case I simply by raising the plant-specific cost G . We then move to Case III by raising G further, and by raising γ as well.

5. Summary and conclusions

A two-region model is developed where a firm can locate plants in one, both or neither region, and where production from the plant(s) causes local pollution. In this world, the two governments compete in terms of the environmental policies. The model differs significantly from the Pigouvian tradition of marginal analysis in competitive models by assuming production with increasing returns to scale and shipping costs between regions. The single firm chooses between the high fixed-cost option of having plants in both of two regions, versus the high variable-cost option of serving both markets from a single plant. There are large jumps in a region's welfare at

critical levels of policy variables where the firm switches the number and location of its plants. In addition to concerning itself with the traditional price and output decisions of the firm, policy must also address discrete-choice problems such as whether to (1) attract a plant to the region, (2) expel a plant due to its environmental externality, and (3) induce the firm to close its foreign plant and serve that foreign market by exports from its local plant.

In this context, pollution taxes affect the firm's choice and therefore regional welfare in two ways. First, generally higher taxes in both regions are, from the firm's point of view, a contraction in effective demand. Thus the firm may shift away from the high fixed-cost option of two plants to the high-variable cost option of a single plant. Second, relatively lower taxes in one region may induce the firm to move its single plant to that region, and/or close its plant in the other region.

Our Case I focusses more on the first effect. In Case I, when both regions impose their individually optimal non-strategic taxes (taxes that are optimal assuming that market structure remains fixed with plants in both regions), the firm chooses a single plant. We then show that the region that does not get the plant has an incentive to cut its taxes, and a tax competition results. A Nash equilibrium with taxes lower than their non-strategic values results, and that equilibrium may either have a single plant or plants in both countries. We presented a numerical example of the latter, in which tax competition results in more plants and pollution.¹³

Our Case II focusses more on the second effect of taxes. In this case when both regions impose their non-strategic taxes, the firm continues to choose two plants. But both regions may have an incentive to under-cut in order to induce the firm to close its foreign plant, if the added tax revenue from export sales exceeds the disutility of added pollution. We derive sufficient conditions for under-cutting to occur and then solve for the non-cooperative equilibrium tax rates. An equilibrium is reached with plants in both regions, but at tax levels lower than the non-strategic levels. The non-cooperative outcome in this case has the right number of plants, but too much pollution.

Our Case III focuses on the NIMBY possibility, in which the Nash equilibrium involves no production of X and no pollution. Yet the joint welfare of the two regions is higher if one of them will accept a plant, an outcome that can be supported by an appropriate transfer payment from the region without the plant. Case III is in a sense opposite to Case I in two respects: in the former, (1) there are too few plants and too little pollution

¹³ Again, this result compares the number of plants at the non-cooperative equilibrium versus the number that are chosen by the firm at the non-strategic rates. It is not clear without further analysis that the non-cooperative equilibrium has too many plants relative to some cooperative outcome that the two counties could achieve given their limited set of instruments.

at the Nash equilibrium instead of too many and too much, and (2) the transfer payment must be from the region without the plant to the region with the plant rather than the other way around as in Case I.

We showed that the three cases are related to one another through the initial values of parameters, and in particular we focussed on the size of fixed costs and the disutility of pollution. Beginning at an ‘intermediate’ value of G and a relatively low value of γ , we have Case II. We can then move to Case I simply by raising the fixed cost G . From Case I, we can move to Case III by raising G further, and by raising the disutility of pollution, γ .

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Appendix

The purpose of this appendix is to demonstrate the assertion made in Cases I and II of Section 4 that a region cannot improve its welfare (at the proposed (1, 1) equilibrium) by induced the firm to shut its other plant by a combination of raising its domestic tax and lowering its export tax (we proved in the text that neither of these things individually are welfare improving). The effect of a small lowering of the export tax and an increase in the domestic tax in Region A that leaves the firm indifferent between (0, 1) and (1, 0) can be divided into the usual marginal effect plus the impact effect of a sudden discrete change in the level of exports (initially zero at the proposed equilibrium). In Cases I and II, $(t_e - \gamma) = 0$ initially, so the impact effect is zero.

Consider then the marginal effect of raising t and lowering t_e . Intuitively, this does not seem to make sense since raising the domestic tax generates a loss of consumer surplus while the combined effects of the two tax changes may leave pollution and tax revenue roughly unchanged.

Note from (8) that profits for the firm with one plant in Region A, (1, 0), can be written as

$$\pi = X_d^2 + X_e^2 - G - F \quad (\text{A1})$$

The minimum amount Region A can lower t_e for a given increase in t without the firm switching to (0, 1) is given by setting the total differential of (A1) equal to zero.

$$2[X_d(dX_d/dt) dt + X_e(dX_e/dt_e) dt_e] = 0 \quad dX_i/dt_i = -1/2 \quad (\text{A2})$$

Substituting the right-hand equation ($i = d, e$) into the left, this condition becomes

$$dt_e = -(X_d/X_e) dt \quad (\text{A3})$$

The effect of the proposed scheme on welfare is given by

$$dW = \left[X_d + (t - \gamma) \right] \frac{dX_d}{dt} + X_d \Big] dt + \left[(t_e - \gamma) \frac{dX_e}{dt_e} + X_e \right] dt_e \quad (\text{A4})$$

Now replace dt_e with (A3) and replace dX_i/dt_i with $-1/2$. Finally, divide through by $dt > 0$. (A4) becomes

$$dW_a/dt = -(X_d/2) - (t - \gamma)(1/2) + (t_e - \gamma)(1/2)(X_d/X_e) \quad (\text{A5})$$

In Cases I and II of Section 4, $(t_e - \gamma) = 0$ and $(t - \gamma) > 0$ initially, so the whole expression in (A5) is negative. At the proposed (1, 1) equilibrium in both cases, Region A cannot improve its welfare by a combined policy of raising its domestic tax and lowering its export tax in order to induce the X producer to shut its plant in Region B. (Note that the argument cannot be reversed to conclude that the domestic tax should be lowered and the export tax raised: at (1, 1) initially, raising t_e has no effect on exports and the domestic tax is already lower than its optimal value.)

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