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Optimal emission tax with endogenous location choice of duopolistic firms*

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Abstract

This paper explores an optimal environmental tax policy when polluting firms strategically choose the location of their plants in a three-stage game. We examine how the relationship between the optimal environmental tax and the plant location choices of duopolistic firms affects the welfare of the home country. We show that even if the duopolistic firms are identical ex ante, an asymmetric equilibrium may emerge in which either of the two firms relocates its plant in the foreign country. We also show that despite the persistence of globalization, the firms move back their relocated plants to the home country, thus causing the resulting welfare to decline.

Keywords: Environmental policy, Globalization, Relocation, Welfare

JEL classification: F18; H 23; L 13;

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1 Introduction

Increasing globalization due to market integration via trade and foreign direct investment (FDI) influences the level of pollution in a country through various channels such as market size, infrastructure, and promotional expenditures to attract foreign investment, input factor costs, tax policy, and environmental regulation. National environmental policies such as environmental standards or taxes, among other things, may influence firms' location choices, more specifically, the plant location decisions of polluting firms. Substantial empirical studies have attempted to test the so-called pollution haven hypothesis (PHH): a reduction in the barriers of trade and FDI leads to a relocation of pollution-intensive industry from countries with stringent environmental regulations to countries with weaker environmental regulations. While this hypothesis is intuitively plausible, empirical literature has concluded that the evidence is mixed. Among the studies, Jaffe et al. (1995) and Eskeland and Harrison (2003) conclude that empirical support for the hypothesis is week at best, while List and Co (2000), Xing and Kolstad (2002), and Dean et al. (2009) have found significant evidence that empirically supports the PHH.

When we look at the theoretical side, there are several papers that investigate the effects of environmental policy on firms' location choices. Markusen et al. (1993) and Motta and Thisse (1994) examine firms' location choices under international oligopoly.[1] Markusen et al. find that a small change in environmental policies may cause the firms to alter their location choices, which gives rise to large discontinuous changes in pollution and welfare levels

[1]The main difference between Markusen et al. (1993) and Motta and Thisse (1994) is that when the game begins, firms have been established in their home country, which implies that fixed set-up (plant) costs are *sunk* in the latter model. Motta and Thisse show that in the presence of large fixed sunk costs, relocation of firms may not be the most natural response to stringent environmental policies.

in the concerned countries. Since there is only one active government that carries out an environmental policy (called a unilateral environmental policy) in their analysis, the strategic nature of the competition among governments in different countries is ignored to determine optimal emission tax rates. In contrast, Markusen et al. (1995), Rauscher (1995), and Hoel (1997), and Greaker (2003) endogenize environmental policies as a Nash equilibrium of a three- (or two-) stage game among governments in a two-region (or two-country) model: in the first stage, the government of each region (or country) strategically chooses environmental policies or emission taxes; in the second stage, the firms decide where to locate; in the third stage, each firm plays a one-shot Cournot output game, thus generating pollution. Furthermore, Petrakis and Xepapadeas (2003) and Ulph and Valentini (2001) analyze a model with time-consistent or ex-post environmental policies, where the two firms (or the monopolist) choose the location of their plants in the first stage and the governments of the two countries strategically set their environmental policies in the second stage.

This paper aims to extend the model of Petrakis and Xepapadeas (2003) with monopolistic market structure to the one with oligopolisitic market structure by simply increasing the number of firms from one to two. Hence, this paper describes a Cournot duopoly model with two polluting *home* firms that strategically choose where to locate their production plants (both in their home country, or both in a foreign country, or one in the home country and the other one in a foreign country), while ignoring the abatement activity of the firms. Our main focus is to employ a *simple diagram apparatus* to conduct an in-depth analysis of the interplay between the cost of relocation and the degree of environmental damages that influence the optimal emission tax and impact domestic welfare. In order to highlight how the optimal emission tax *endogenously* selected by the government depends on these location factors, the simplest case will be considered, that is, *unilateral environmental policies* carried out only by the government in the country where the firms are initially located, following Markusen et al. (1993), Motta and Thisse (1994), Petrakis and Xepapadeas (2003), and Kayalica and Lahiri (2005). We develop the following three-stage game. In the first stage, only the home government sets the emission tax rate to maximize domestic welfare. In the second stage, given the tax rate, the duopolistic firms choose the location of their plants. In the third stage, we show how the duopolistic firms compete in the market á la Cournot by choosing their output levels, given an emission tax rate and their location choices. Furthermore, we address the same issue under the regime of time-consistent (or ex post) emission taxation in which the government sets the ex post optimal emission tax conditioned on the realized location choices of the duopolistic firms.

The contributions of this paper are fourfold. First, there exists an *asymmetric* location equilibrium of the Cournot duopoly model in which one firm sets its plant in the home country, while another firm relocates its plant to the foreign country. The novelty is that such an asymmetric equilibrium may arise when the two firms that are *ex ante identical in all respects* choose a different location. This stands in sharp contrast with the result of Petrakis and Xepapadeas (2003), in which a monopolist simply relocates only when combinations between the degree of environmental damage and the size of relocation costs are situated above a certain boundary, while it does not relocate below this boundary. Hence, their setting does not allow for such an asymmetric location equilibrium.[2]

Second, we show how alterations in the degree of damage from emissions and the size of relocation costs affect the optimal emission tax and domestic welfare through the location decisions of firms. Many variations in the patterns of location and welfare levels emerge in equilibrium as compared to those in Motta and Thisse (1994) and Petrakis and Xepapadeas (2003). When the degree of damage is sufficiently small, the optimal emission tax is negative (i.e., it turns into a subsidy) irrespective of the size of relocation costs. When the degree of damage from pollution is moderate, the optimal emission tax either remains constant or is generally increasing with the cost of relocation. Moreover, it is more likely not only that the asymmetric location equilibrium emerges, but also that the firms may move back their relocated plants to the home country (i.e., the firms do not want to relocate abroad) even under lower relocation costs. When the environmental damage is large enough, the government always drives both firms out by setting a higher emission tax irrespective of the size of relocation cost. This situation would correspond to the one described by the PHH. Particularly noteworthy is the finding in that *when the environmental damage is moderate, i.e., environmental policies are loose, all domestic firm may relocate abroad, which would contradict with the* PHH.

Following most of the existing literature, we define domestic welfare as the sum of consumer surplus, the profits of domestic firms, tax revenues, and environmental damage. By using this welfare function, we find that the level of welfare varies according to the relocation patterns of firms which are jointly determined by the relocation cost and the cost of environmental

[2] Motta and Thisse (1994) do not allow for such an asymmetric location equilibrium because there is only one polluting firm that is freely mobile across countries.

damage through the optimal emission tax. When both firms remain in the home country, the government enjoys large profits and tax revenue from the two firms as well as consumer surplus, but it suffers from huge environmental damage. When either firm relocates its production abroad, the benefits from tax revenue and profits decrease while the benefits from the reduction in environmental damage and the consumer surplus due to price reduction increase. Although the optimal emission tax is *non-decreasing* with the cost of relocation, the consequent domestic welfare varies with it in a *non-monotonic way.* Non-monotonical welfare changes are due to the switching of the governmental objective welfare functions that reach the highest level at different tax levels in response to the firms' location choices. In other words, these non-monotonic welfare changes imply that tough environmental policies may improve welfare, which has not been addressed by Ulph and Valentini (2001) and Petrakis and Xepapadeas (2003).

Third, we also consider the model with a time-consistent (ex post) tax policy in which the firms first decide whether to locate in the home country or not. In this case, the government always chooses the *second-best* emission tax rate that maximizes domestic welfare, given the predetermined location choices of the firms. We show not only that the government can achieve higher welfare as compared to the welfare under the previous model with precommitted (ex ante) emission taxes, but also that *the welfare levels are monotonically decreasing in the relocation cost* unlike those in the previous model. These results stem from the fact that higher relocation costs make the firms more difficult to relocate abroad, which enables the government to impose higher emission tax rates. These results have not been addressed by the models with time-consistent environmental policies of Ulph and Valentini

(2001) and Petrakis and Xepapadeas (2003).

Fourth, we investigate how the globalization of the world economy influences the government optimal environmental policy and the resulting welfare. For the last few decades, the world economy has been experiencing waves of globalization. With the ongoing globalization, various costs that economic resources incur in moving across national borders have been drastically declining. In this paper, the relocation cost measures the degree of globalization. That is, the higher the degree of globalization, the lower is the relocation cost. It is expected that under globalization, the domestic firms are inclined to relocate their plants abroad, thus improving the welfare. We, however, show that *for intermediate values of the degree of damage*, the firms move back their once relocated plants to the home country as globalization proceeds. Hence, the welfare levels do *not* monotonically change in response to the progress of globalization because of the switch in the governmental objective welfare functions caused by the induced location changes of firms.

The rest of the paper is organized as follows. In section 2, we develop our game model with three stages. We derive and characterize the optimal emission tax rate, the equilibrium location, and the resulting welfare level by backward induction in sections 3 and 4. In section 5, we discuss how globalization influences the equilibrium location and the resulting welfare level. Section 6 performs the same task when the government cannot commit to ex ante tax policy. Section 7 gives brief concluding remarks.

2 Model

Consider two countries, country H (i.e., a home country) and country F (i.e., a foreign country). We assume that two identical firms produce and sell a homogeneous good in the market of country H. For analytical simplicity, we assume that country F has no market.[3] The production cost functions of these two firms are assumed to be the same and given by $C(q_i) = cq_i$, where q_i is the output of firm $i = 1, 2$. The firms face a demand, $P(q) = a - q$, where a stands for the market size and q is the market demand for the product. Pollution is generated in the good's production process. The damage function is given by $D(x) = dx^2/2$, where d is a damage coefficient that may be viewed as the preference of consumers toward the environmental quality of home country (i.e., country H) and x denotes the firms' total emissions in country H. We assume that one unit of production generates one unit of pollution. We also assume not only that both firms, which are initially located in the home country H, are subject to the environmental policy in country H and can relocate their production plants from country H to F with the cost of relocation f, but also that the relocating firm exports its product to country H *without transportation costs*. For analytical simplicity,

[3] The literature on environmental policies and endogenous plant location contains several modes of introducing the market of output. Ulph and Valentini (2001) and Kayalica and Lahiri (2005) assume the existence of the good market in a third country where any firm does not locate. Petrakis and Xepapadeas (2003) assume that after its relocation, the monopolist exports its product to the home country. Our approach can be thought of as an extreme case of this strategy in which country F has no market. The introduction of an explicit market of goods in country F strengthens the incentive of firms to relocate their plant in country F without environmental policy. In response, the government of the home country H has to impose a lower environmental tax rate in order to retain firms, thereby decreasing the optimal tax rate. As a result, it is more likely that plant relocation to country F takes place even if the relocation cost f and environmental tax rates are the same as before. In short, the introduction of an additional market would complicate the analysis without adding further insights; hence, we ignore it.

it is further assumed that the firm's profits remain in country F.[4]

3 Equilibrium: Firms Locate After Governments Set Taxes

We derive a subgame perfect Nash equilibrium of the three-stage game outlined in the introduction of the paper by using backward induction when the government can commit to an emission tax rate *ex ante*. We will consider the model with the reversed timing of the order in Section 6.

3.1 Output decision: Third-stage game

In the last stage, given an emission tax set by the home government and the location choice of each firm in the previous stages, each firm chooses its

[4]In the literature on environmental policies and endogenous plant location there are several ways to distribute the profits earned by foreign affiliations. Markusen et al. (1993) assume that all the profits go to owners outside the concerned countries; hence, the profits of the firms are not included as a component of the social welfare function. Ulph and Valentini (2001) and Petrakis and Xepapadeas (2003) assume that profits accrue to the country of production (i.e., where plants are located). Motta and Thisse (1994), Hoel (1997) and Kayalica, and Lahiri (2005), on the other hand, assume that a fixed proportion of profits flow to the home country, whose proportion might reflect the ownership share of the firm or the efforts of the multinational corporations not only to minimize their tax liabilities at home, but also to finance their foreign operations and their foreign investment. Although the last assumption might be the most natural one, depending on the magnitude of this proportion, we could potentially obtain a variety of results regarding the welfare impacts of environmental policies. Hence, we just consider an extreme case where profits accrue to the country of production because of lack of space.

On the other hand, recent trends in Foreign Direct Investment show increasing cash holdings by the foreign affiliates of multinational corporations. According to the world investment report of UNCTAD (2012), although outward FDI from developed countries has been increasing and reaching $1.24 trillion, the amount of cash reserves retained in foreign affiliates has also increased. In the U.S.A., reinvested earnings of foreign affiliates reached a record $326 billion in 2011, accounting for 85 per cent of FDI outflows. The report of Ministry of Economy, Trade and Industry, Japan also summarizes that the amount of current retained earnings significantly increased, although payments to Japan remained nearly unchanged. Thus, based on the increasing tendency of this proportion, we can ignore the location of the two firms' ownership, which crucially affects the welfare impacts of environmental policies, although our assumption would be a limiting case.

output to maximize profits. First, suppose that both firms remain in country H. Firm i's profit maximization problem is

$$\max_{q_i} \quad (a - q)q_i - cq_i - tq_i, \quad i = 1, 2,$$

where t denotes the tax per unit of emissions. Solving the first order conditions of the two firms for profit maximization simultaneously yields the Cournot-Nash equilibrium outputs of the firms:

$$q_1 = q_2 = \frac{1}{3}(A - t), \tag{1}$$

where $A \equiv a - c > 0$. The aggregate output is $q = q_1 + q_2 = 2(A - t)/3$, so that the equilibrium profit of firm $i = 1, 2$ is

$$\pi^i_{HH} = \frac{1}{9}(A - t)^2 \equiv \pi_{HH}. \tag{2}$$

If both firms relocate their production plants to country F and supply their products in the market of country H, firm i's profit maximization problem is given by

$$\max_{q_i} \quad (a - q)q_i - cq_i - f, \quad i = 1, 2.$$

Similarly, the equilibrium outputs of the firms are given by

$$q_1 = q_2 = \frac{1}{3}A. \tag{3}$$

The aggregate output is $q = q_1 + q_2 = 2A/3$ and the resulting profit of firm $i = 1, 2$ is

$$\pi^i_{FF} = \frac{1}{9}A^2 - f \equiv \pi_{FF}. \tag{4}$$

Finally, if firm 1 remains in country H while firm 2 relocates its own plant to country F, the equilibrium outputs of the two firms are given by

$$q_1 = \frac{1}{3}(A - 2t) \quad \text{and} \quad q_2 = \frac{1}{3}(A + t). \tag{5}$$

In this case, the aggregate output is $q = q_1 + q_2 = (2A - t)/3$, and the respective equilibrium profits of the firms are given by

$$\pi^1_{HF}(= \pi^2_{FH}) = \frac{1}{9}(A - 2t)^2 = \pi_{HF} \quad \text{and} \quad \pi^2_{HF}(= \pi^1_{FH}) = \frac{1}{9}(A + t)^2 - f = \pi_{FH}. \tag{6}$$

We make the following assumptions in order to ensure that the equilibrium outputs and profits of both firms are nonnegative (recall (2), (4), (5) and (6)):

Assumption 1: $A \equiv a - c > 0$, $t \in [-A, A/2]$ and $f \in [0, A^2/9]$.

Note that the socially optimal emission tax rate, t, can take a negative value because we allow for subsidies such as the one for pollution abatement.

3.2 Location choice: Second-stage game

In the second stage, the duopolistic firms make the location decisions, given an emission tax rate in country H and their rival's strategy about the location of its plant; each firm has two location strategies H (remain in country H) and F (relocate to country F). From (2), (4), and (6), we can summarize this location game by the payoff matrix depicted in Table 1, each of whose cells represents a pair of the profits earned by both firms:

	firm 2	
firm 1	H	F
H	π_{HH}, π_{HH}	π_{HF}, π_{FH}
F	π_{FH}, π_{HF}	π_{FF}, π_{FF}

Table 1: Payoff matrix

There can be three location equilibria: HH, FF, and HF (or FH). Let us compare the payoffs to derive the equilibrium conditions for the respective cases. First, consider the case where HH is an equilibrium. Given firm 2's strategy H, the condition under which firm 1 has no incentive to relocate its plant to country F is

$$\pi_{HH} \geq \pi_{FH} \quad \Leftrightarrow \quad f \geq \frac{4}{9}At.$$

Next, we consider the case FF. Given firm 2's strategy F, the condition under which firm 1 has no incentive to remain in country H is

$$\pi_{FF} \geq \pi_{HF} \quad \Leftrightarrow \quad f \leq \frac{4}{9}(A-t)t.$$

Finally, consider the *asymmetric* case HF. Given firm 2's strategy F, the condition under which firm 1 decides to remain in country H is

$$\pi_{HF} \geq \pi_{FF} \quad \Leftrightarrow \quad f \geq \frac{4}{9}(A-t)t.$$

When firm 2 chooses strategy H, the condition under which firm 1 decides to relocate its plant to country F is

$$\pi_{FH} \geq \pi_{HH} \quad \Leftrightarrow \quad f \leq \frac{4}{9}At.$$

When the profits associated with the respective cases are equal (i.e., payoff ties occur), the location choices of the firms are *indeterminate*. To avoid this case, we make the following assumption:

Assumption 2: *When a firm is indifferent between the two locations, this firm chooses a location that gives higher welfare for the home country.*

By jointly considering the above conditions, we can identify the following three location equilibria depending on the relocation cost f:

Proposition 1 *Under Assumptions 1 and 2, we have*

(i) If $f < (4/9)(A-t)t$, then both firms relocate their plants to country F.

(ii) If $(4/9)(A-t)t \leq f < (4/9)At$, then one firm remains in country H, while the other firm relocates to country F.

(iii) If $(4/9)At \leq f \leq A^2/9$, then both firms remain in country H.

INSERT FIGURES 1

Solving the boundary conditions where the firm is indifferent between the two locations for t, $f = (4/9)At$ and $f = (4/9)(A-t)t$, yields the *maximum* *tax rate* $t_{HH}(f)$ at which both firms remain in country H and the *maximum tax rate* $t_{HF}(f)$ at which either firm relocates to country F, respectively:

$$t_{HH}(f) = \frac{9f}{4A} \text{ and } t_{HF}(f) = \frac{A - \sqrt{A^2 - 9f}}{2}.$$

Moreover, by varying values of f, we can draw the curves $t_{HH}(f)$ and $t_{HF}(f)$ in $f - t$ space, as depicted in Figure 1. Figure 1 also indicates the *Nash equilibrium* location choices of the two firms for various combinations between the values of t and f. When the emission tax, t, is low and the relocation cost, f, is high, both firms are willing to remain in the home country H (i.e., region (H, H) in Figure 1), while when the emission tax is high and the relocation cost is low, both firms have an incentive to relocate their plants to country F (i.e., region (F, F) in Figure 1).

When both the emission tax and the cost of relocation are medium, either of the two firms relocates to country F (i.e., region (H, F) or (F, H) in Figure 1). If the firm located in country H *unilaterally* relocates abroad, then the plants of both firms will be situated in country F. Consequently, the two firms expand their production owing to the absence of emission taxes, leading to a fall in the market price, thus depressing the profits of both firms. On the other hand, if the firm with foreign production *unilaterally* chooses production in country H, then the plants of both firms will be situated in country H. This causes the output of that firm to fall due to the tax burden imposed by the government of country H, thus resulting in a lower profit. Hence, there is no incentive for either of the firms to alter its current location choice.

3.3 Environmental policy decision: First-stage game

In the first stage, *anticipating* the equilibrium outcomes of the subsequent stages, the government of the home country H chooses an (precommitted) emission tax rate t so as to maximize the social welfare of country H. The welfare is defined as the sum of consumer surplus, the profits of the firms remaining in country H, the tax revenue, and the damage from pollution (negative externalities). The welfare is clearly affected by the location choices of the duopolistic firms, which in turn depend on the environmental policy (i.e., the emission tax rate t) set by the government of country H. When both firms remain in country H, the welfare is defined as

$$W_{HH} \equiv CS_{HH} + \pi^1_{HH} + \pi^2_{HH} - D(q) + tq,$$

where $CS_{HH} \equiv \int_0^q p(s)ds - p(q)q$ is the consumer surplus of country F in the equilibrium HH. When one of the firms, say i, remains in country H and the other firm relocates to country F, the welfare is expressed by

$$W_{HF} \equiv CS_{HF} + \pi^i_{HF} - D(q_i) + tq_i, \quad i = 1, 2.$$

In this case, the profit and emission tax revenue of the firm that remains in country H and the damage cost from the emissions of its production are included. When both firms relocate to country F, the welfare is

$$W_{FF} \equiv CS_{FF},$$

where neither the tax revenue nor the damage cost appears in the welfare function.

Substituting (1)–(6) into the respective definitions of welfare, we obtain three reduced forms for the welfare functions as follows:

$$W_{HH}(t;d) \equiv \frac{2}{9}\left[-(1+d)t^2 - (1-2d)At + (2-d)A^2\right], \tag{7}$$

$$W_{HF}(t;d) \equiv \frac{1}{18}\left[(6-d)A^2 - (6-4d)At - (3+4d)t^2\right], \tag{8}$$

$$W_{FF}(t;d) \equiv \frac{2}{9}A^2. \tag{9}$$

Given the value of d, the welfare functions (7) and (8) are inverse U-shaped (i.e., single peaked) in t, while (9) takes a constant value independent of t.[5] The underlying intuition for the shapes of the welfare functions (7) and (8) is as follows. Both welfare functions consist of four components: consumer surplus, the profit(s) of the domestic firm(s), tax revenue, and damage cost, the former three of which are functions of t with the damage cost being indirectly affected by the emission tax through a change in the domestic production. On the one hand, given d, an increase in t reduces domestic production and thus consumer surplus; consequently, the damage cost and the gross profit monotonically decrease at an increasing rate as t becomes higher. On the other hand, an increase in t raises the tax revenue when the tax rate is low and reduces the revenue after the tax rate exceeds $A/4$ in the HF case. Accordingly, when the tax rate is low, the positive effect of an increase in t on the tax revenue is sufficient to overcome the negative effects of the other components. As tax rate becomes high, the other components decrease at an increasing rate; consequently, tax revenue starts to decline after the tax rate reaches its threshold value (i.e., $A/4$),

[5] Since the functions $W_{HH}(t;d)$ and $W_{HF}(t;d)$ are concave in t and since the coefficients of t^2 in (7) and (8) are negative with $\lim_{t\to\pm\infty} W_{HH}(t;d) = \lim_{t\to\pm\infty} W_{HF}(t;d) = -\infty$, these functions are inverse U-shaped in t.

which results in an inverse U-shaped welfare function of t for any d.

Given the inverse U-shaped welfare functions of t, the *optimal emission tax* rates that maximize W_{HH} and W_{HF} are respectively given by

$$\widetilde{t}_{HH}(d) = \frac{(2d-1)A}{2(1+d)} \quad \text{and} \quad \widetilde{t}_{HF}(d) = \frac{(2d-3)A}{3+4d}. \tag{10}$$

It is immediate that $\widetilde{t}_{HH}(d) > \widetilde{t}_{HF}(d)$ for $0 \leq d < 15/7$.[6] This implies that *the peak of the function W_{HH} lies to the right of the peak of the function W_{HF}*. The government in the HH case wants to obtain a larger tax revenue and a lower damage cost. As a result, the government then sets a higher tax rate until the negative effects of the reduction in domestic production and consumer surplus dominate the positive effect of a higher tax rate. In the HF case, the government bears a lower damage cost and gains the tax revenue and profit earned by only one firm in addition to the consumer surplus that depends positively on the *aggregate* level of output. In this case, the negative effect of a higher tax on consumer surplus dominates its positive effect. Therefore, *given any d, the optimal tax rate in the HF case is always lower than that in the HH case.*

Consider the effect of a change in the marginal damage coefficient d on W_{HH} and W_{HF} given t, while W_{FF} remains unchanged. Since the damage cost, $D(x) = dx^2/2$, is directly affected by d, an increase in d shifts the curves of W_{HH} and W_{HF} downward (see (A.1) in the Appendix). The government with a higher d wants to reduce more pollution than the government with a lower d does. Therefore, as d becomes larger, the government wants to set a higher optimal emission tax, which in turn shifts the welfare functions

[6] When $d > 15/7$, the welfare function W_{FF} is the largest for any emission tax rate, and thus, emission taxes are abolished.

rightward. Combining these observations, the welfare functions shift downward to the right as d increases. Figures 2–7 illustrate the locations of three welfare functions with respect to different values of d.

3.4 Welfare comparison

We need to rank the welfare levels for various values of d and f. To this end, in this section, we will draw several diagrams that summarize the relative position of three welfare functions (7)–(9) with respect to the emission tax rate t and the cost of relocation f, given various values of the marginal damage coefficient d.

First, subtracting (7) from (9) yields $W_{FF} - W_{HH} = (2/9)g_1(t; d)$, where

$$g_1(t; d) \equiv (1 + d)t^2 - (2d - 1)At + (d - 1)A^2. \tag{11}$$

When $d < 5/4$, the quadratic equation $g_1(t; d) = 0$ has two distinct real roots, denoted by t_2 and $t_5(> t_2)$: $A\left(2d - 1 \pm \sqrt{5 - 4d}\right)/2(1+d)$. The roots t_2 and t_5 denote the tax rates at which the curves W_{HH} and W_{FF} intersect each other (i.e., $W_{HH} = W_{FF}$). Using this fact together with Lemma 3, we can draw Figure 5.

Subtracting (8) from (9), we obtain $W_{FF} - W_{HF} = g_2(t; d)/18$, where

$$g_2(t; d) \equiv (4d + 3)t^2 - (4d - 6)At + (d - 2)A^2. \tag{12}$$

When $d < 15/7$, the quadratic equation $g_2(t; d) = 0$ has two distinct real roots, one of which is negative, t_1, and the other is positive, $t_4(> t_1)$: $A\left(2d - 3 \pm \sqrt{15 - 7d}\right)/(4d + 3)$. The roots t_1 and t_4 denote the tax rates at which the curves W_{FF} and W_{HF} intersect each other (i.e., $W_{FF} = W_{HF}$). By using this fact together with Lemmas 3 and 4, we can draw Figure 6.

Comparing (8) with (7) yields $W_{HH} - W_{HF} = g_3(t; d)/18$, where

$$g_3(t; d) \equiv -t^2 + (4d + 2)At - (3d - 2)A^2. \tag{13}$$

The quadratic equation $g_3(t; d) = 0$ has two distinct real roots, one of which may be positive or negative, t_3, and the other is positive, t_6: $A\left(2d + 1 \pm \sqrt{4d^2 + d + 3}\right)$. The roots t_3 and t_6 denote the tax rates at which the curves W_{HH} and W_{HF} intersect each other (i.e., $W_{HH} = W_{HF}$). By using this fact together with Lemmas 2 and 3, we can draw Figures 4 and 5.

4 Location choices of firms and welfare

With the help of Figures 2–7, we are now ready to derive an optimal emission tax rate chosen by the government of country H depending on values of the degree of environmental damage d and the relocation cost f.

4.1 Case of small d

Let us first examine the case where the damage coefficient d is small, or equivalently, the preference toward environmental quality is relatively weak. It seems that this case occurs in developing countries. Figures 2 and 3 illustrate the optimal emission tax and the associated welfare level of country H for $0 \leq d \leq 2/3$.

INSERT FIGURES 2 AND 3

Since it follows from Lemma 1 of the Appendix that W_{HH} is always the largest among (7)–(9) for $0 \leq d \leq 2/3$, the government of country H chooses an emission tax rate so as to maximize W_{HH}. Thus, with the help of Figures 2 and 3, we can demonstrate the following proposition:

Proposition 2 *Under Assumptions 1 and 2,*

(i) When $0 \leq d \leq 1/2$, the optimal emission tax rate is non-positive (i.e., subsidy):

$$\tilde{t}_{HH}(d) = \frac{(2d-1)A}{2(1+d)} < 0,$$

where $\tilde{t}_{HH}(0) = -A/2 < 0$ and $\tilde{t}_{HH}(1/2) = 0$.

(ii) When $1/2 < d \leq 2/3$, the optimal emission tax rate is set according to $t_{HH}(f) \equiv 9f/(4A) > 0$ for $f \in [0, \tilde{f}]$, while it takes a constant value, i.e., $t_{HH}(\widetilde{f}) \equiv 9\widetilde{f}/(4A) > 0$ for $f \in [\tilde{f}, A^2/9]$, where $\widetilde{f}$ satisfies the equality $\widetilde{t}_{HH}(d) = t_{HH}(\widetilde{f})$ (i.e., $(2d-1)A/2(1+d) = 9\widetilde{f}/(4A)$) for a given value of d.

(iii) The location pattern of firms is HH for $d \in [0, 2/3]$ and $f \in [0, A^2/9]$.

If emissions incur no damage on the environment (i.e., $d = 0$), or environmental damage is sufficiently small (i.e., $0 < d \leq 1/2$), the government is willing to retain both firms and thus induce them to expand their production by subsidizing emissions at the welfare-maximizing rate, $\tilde{t}_{HH}(d) < 0$, so as to make the profits of the two firms larger. As a result, the consumer surplus is also increased owing to a price reduction caused by a larger supply of output. The reason for providing subsidies is that the output levels chosen by the firms are too small from a welfare viewpoint; in other words, there are distortions associated with imperfect (Cournot) competition that tend to dominate the damage cost. This is depicted in Figure 2.

On the other hand, when the environmental damage is not sufficiently small (i.e., $1/2 < d \leq 2/3$), it is no longer optimal for the government to subsidize the polluting firms. Nevertheless, *W_{HH} is still the largest as depicted in Figure 3*. In this case, the government will impose a positive emission tax according to $t_{HH}(f)$ for $f \in [0, \widetilde{f}]$, *the largest tax rate for the firms that remain in country H*, because the tax revenue largely contributes to the welfare of country H; thus, the government wants to retain both firms. When the relocation cost f exceeds its threshold value $\widetilde{f}$, the government of country H continues to set the largest (and same) tax rate, $t_{HH}(\widetilde{f}) = \widetilde{t}_{HH}(d)$, since W_{HH} is decreasing in t for $t > t_{HH}(\widetilde{f})$. The decrease in W_{HH} arises because of the dominating decrease in consumer surplus caused by higher tax rates.

4.2 Case of medium d

Next, we look at the case where the damage coefficient d takes a medium value (i.e., $2/3 \leq d < 5/4$). This category can be considered as the case of most developed countries, such as the U.S.A., U.K., Germany, and Japan. The left panel of Figure 4 illustrates how the optimal emission tax is determined, while the right panel illustrates the relationship between the optimal emission tax and the relocation cost, as well as the relationship between the maximized welfare and the relocation cost, when $2/3 < d \leq d^*$, where d^* represents the threshold value at which $W_{HH}(t_3; d^*) = W_{HF}(t_3; d^*) = W_{FF}$. It should be stressed that *the maximized welfare level constrained by the location choices of firms is not monotonic with the cost of relocation f*, as illustrated in the right panel of Figure 4, unlike the case of $0 \leq d \leq 2/3$ (recall Figures 2 and 3).

INSERT FIGURE 4

For $f \leq f_3$ (noting that f_3 is given by $t_3 = t_{HH}(f_3)$, where t_3 corresponds to the tax rate at which $W_{HF}(t_3; d) = W_{HH}(t_3; d)$), the government chooses the optimal emission tax rate according to $t_{HH}(f)$ so as to realize the location pattern of HF (recall Assumption 2), and thus, W_{HF}, since a gain in consumer surplus resulting from a larger amount of exports dominates the reduction in profits and the tax revenue due to the relocation of firm. Hence, W_{HF} is the largest in $f \in [0, f_3]$ as depicted in Figure 4.

For $f_3 \leq f < \widetilde{f}$ (noting that $\widetilde{f}$ satisfies $\widetilde{t}_{HH}(d) = t_{HH}(\widetilde{f})$ for a given d), the government sets the tax rate according to $t_{HH}(f)$ so as to retain both firms in country H since $W_{HF} < W_{HH}$ as depicted in Figure 4. In this range, the government enjoys the tax revenue and thus can reduce the damage cost by setting a higher tax rate. When the cost of relocation reaches $\widetilde{f}$, the government chooses $t_{HH}(\widetilde{f}) = \tilde{t}_{HH}(d)$ which maximizes W_{HH}. If the relocation cost is higher than $\widetilde{f}$, both firms are reluctant to relocate their production plants even for higher optimal tax rates. However, a very high tax rate reduces the outputs of the domestic firms, thereby depressing their profits and consumer surplus. These reductions would dominate the increased tax revenue, which leads to a decrease in W_{HH}. Accordingly, it is optimal for the government to fix the emission tax rate at $t_{HH}(\widetilde{f})$ for $f \geq \widetilde{f}$ as depicted in the right panel of Figure 4.

To summarize:

Proposition 3 *When $2/3 \leq d < d^*$, under Assumptions 1 and 2, the optimal emission tax rates are given by (i) and (ii):*

(i) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [0, \tilde{f}]$

(ii) $\tilde{t}_{HH}(d) = (2d-1)A/2(1+d) > 0$ *for* $f \in [\tilde{f}, A^2/9]$.

(iii) The location pattern of firms changes from HF to HH with f.

INSERT FIGURE 5

Consider the case where $d^* < d < 5/4$. For a relatively small relocation cost, that is, $f \in [0, f_4]$ (noting that f_4 satisfies $t_4 = t_{HH}(f_4)$ with t_4 being the tax rate at which $W_{HF}(t_4; d) = W_{FF}$), W_{HF} is the largest as depicted in Figure 5. Hence, the government wants to retain only one firm to enjoy the benefits from tax revenue and profits for the domestic firm, while it bears environmental damage from its production. Since the negative effect of the decreased consumer surplus caused by higher emission taxes dominates the positive effect of the decreased damage, a higher emission tax rate reduces the consumer surplus as a result of the decreased domestic production. Consequently, the government is forced to choose the lowest tax rate such that only one firm relocates; that is, $t_{HH}(f)$.[7]

For a moderate relocation cost, $f \in [f_4, f_2]$, where f_2 satisfies $t_2 = t_{HH}(f_2)$ with t_2 being the tax rate at which $W_{HH}(t_2; d) = W_{FF}$ and W_{HF} is smaller than W_{FF} (see Figure 5). Accordingly, the government sets $t_{HF}(f)$ to keep

[7]Note that the government has to make the optimal tax rate jump up from $t_{HH}(f_4)$ to $t_{HF}(f_4)$ at point a in Figure 5.

both firms away from the home country (recall Assumption 2), since the government with $d > d^*$ is more conscious about the environmental damage compared to the less conscious government with $d < d^*$.[8] In this case, the government enjoys benefits from the improved environment and the price reduction caused by a larger output, although it sacrifices tax revenues and profits since there is no firm in country H. This case would be consistent with the PHH because the tax rate $t_{HF}(f)$ is not high. More interestingly, once the relocation cost exceeds f_2, the government sets the emission tax $t_{HH}(f)$ in order to retain both firms, because $W_{HH} > W_{FF}$. Intuitively, since the high relocation cost prevents any firm from relocating its plant, the government can impose higher emission tax rates on the domestic firms to obtain a larger amount of the tax revenue. Since setting $t > t_{HH}(\widetilde{f}) = \tilde{t}_{HH}(d)$ reduces W_{HH} due to a reduction in aggregate production, the government is willing to maintain the same tax rate $t_{HH}(\widetilde{f}) = \tilde{t}_{HH}(d)$ for $f > \widetilde{f}$. We summarize the above to obtain the following proposition:

Proposition 4 *When $d^* < d < 5/4$, under Assumptions 1 and 2, the optimal emission tax rates are given by (i)–(iv):*

(i) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [0, f_4]$

(ii) $t_{HF}(f) = (A - \sqrt{A^2 - 9f})/2 > 0$ *for* $f \in [f_4, f_2]$

(iii) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [f_2, \widetilde{f}]$

(iv) $t_{HH}(\widetilde{f}) = 9\widetilde{f}/(4A) = \tilde{t}_{HH}(d)$ *for* $f \in [\widetilde{f}, A^2/9]$

[8] When the relocation cost reaches f_2, the government wants both firms to stay in the home country H. To this end, the government has to make the optimal tax rate jump down from $t_{HF}(f_2)$ to $t_{HH}(f_2)$ at point b in Figure 5.

(v) *The location pattern of firms changes with* f *as follows:* $HF \Longrightarrow FF \Longrightarrow HH$.

INSERT FIGURE 6

When $5/4 \leq d$, the environmental damage is too high, the government is reluctant to keep both firms in the home country, and thus, the welfare W_{HH} is *never* the largest (see Figures 6 and 7). The upper panel of Figure 6 shows the case where $5/4 \leq d \leq 2$. In this case, for $f \in [0, f_4]$, where f_4 satisfies $t_4 = t_{HH}(f_4)$ with t_4 being the tax rate at which $W_{HF}(t_4; d) = W_{FF}$, the government wants to induce only one firm to relocate because W_{HF} is the largest for $t \in [0, t_4]$ as depicted in the upper panel of Figure 6. Moreover, while W_{HF} increases with $t \in [0, \widetilde{t}_{HF}(d)]$, it decreases with $t \in [\widetilde{t}_{HF}(d), t_4]$. Hence, until the relocation cost reaches $\widetilde{f}_{HF}$, which satisfies $\widetilde{t}_{HF}(d) = t_{HF}(\widetilde{f}_{HF})$, the government sets an emission tax according to $t_{HF}(f)$ and then maintains the same welfare-maximizing rate $\widetilde{t}_{HF}(d) = t_{HF}(f)$ for $f \in [\widetilde{f}_{HF}, \widetilde{f}_{HH}]$, where $\widetilde{f}_{HH}$ satisfies $\widetilde{t}_{HH}(d) = t_{HH}(\widetilde{f}_{HH})$. When the relocation cost exceeds $\widetilde{f}_{HH}$, W_{HF} decreases with t due to a decrease in production, which induces the government to set the tax according to $t_{HH}(f)$. Once the relocation cost exceeds f_4, W_{HF} is smaller than W_{FF}. In this case, the government drives both firms out by raising the tax up to $t_{HF}(f)$, which would be consistent with the PHH.

In contrast, the case where $2 < d \leq 15/7$ would not be consistent with the PHH. For $f \in [0, f_1]$, W_{FF} is the largest, as depicted in the lower panel of

Figure 6. Hence, the government sets $t_{HF}(f)$ to drive both firms out, despite the fact that the emission tax rate $t_{HF}(f)$ is not high. For the remaining range of f, the government chooses the same optimal tax rates as those for the previous case where $5/4 \leq d \leq 2$.

We may summarize the above arguments as the following two propositions:

Proposition 5 *When* $5/4 \leq d \leq 2$*, under Assumptions 1 and 2, the optimal emission tax rates are given by (i)–(v):*

(i) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [0, \tilde{f}_{HF}]$.

(ii) $t_{HF}(f) = (A - \sqrt{A^2 - 9f})/2 = \tilde{t}_{HF}(d) > 0$ *for* $f \in [\tilde{f}_{HF}, \tilde{f}_{HH}]$.

(iii) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [\tilde{f}_{HH}, f_4]$.

(iv) $t_{HF}(f) = (A - \sqrt{A^2 - 9f})/2 > 0$ *for* $f \in [f_4, A^2/9]$.

(v) The location pattern changes from HF *to* FF *with* f.

Proposition 6 *When* $2 \leq d \leq 15/7$*, under Assumptions 1 and 2, the optimal emission tax rates are given by (i)–(iii):*

(i) $t_{HF}(f) = (A - \sqrt{A^2 - 9f})/2 > 0$ *for* $f \in [0, f_1]$

(ii) $t_{HH}(f) = 9f/(4A)$ *for* $f \in [f_1, \tilde{f}_{HF}]$

(iii) The statements (ii), (iii), and (iv) of Proposition 5 hold for the remaining ranges of f.

(iv) The location pattern changes with f as follows: $FF \implies HF \implies FF$.

4.3 Case of large d

In the case of a large degree of damage (i.e., $d > 15/7$), W_{FF} *is always the largest* as depicted in Figure 7. This case can be considered as that of Northern European countries such as Norway and Sweden, which are very sensitive to environmental quality. The intuition is simple. The environmental damage caused by the domestic production is so serious that the government has a greater incentive to drive both firms out. As a result, the government always sets the minimum tax rate $t_{HF}(f)$ to prevent the plants owned by either or both of the firms from moving back to the home country H. Hence, this case apparently corresponds to the situation described by the PHH regardless of the size of relocation cost.

Proposition 7 *When $d < 15/7$, under Assumptions 1 and 2, the optimal emission tax rates are given by (i):*

(i) $t_{HF}(f) = 9f/(4A)$ for $f \in [0, A^2/9]$.

(ii) The location pattern of firms is always FF independently of f.

INSERT FIGURE 7

5 Globalization and economic welfare

We can view the relocation cost, f, *as an inverse measure of the degree of globalization in the world economy.* Namely, globalization tends to reduce f. Based on the previous arguments, we can identify the impacts of globalization (i.e., a reduction in f) on domestic welfare under three different ranges for d.

(i) Case of small d: $0 \leq d \leq 2/3$.

The equilibrium location pattern HH remains unchanged even if f decreases (recall Proposition 3). With a very small $d \in (0, 1/2)$, the welfare W_{HH} is maximized for a negative and constant tax rate (i.e., subsidies) and thus is independent of f, as shown in the upper panel of Figure 2. For $d \in [1/2, 2/3)$, on the other hand, the welfare W_{HH} declines as f becomes smaller, as shown in the upper panel of Figure 3. In this case, if a firm moves its plant to the foreign country F, the welfare is reduced to W_{HF}. To avoid this welfare reduction from relocation, the government is obliged to reduce the tax rate according to $t_{HH}(f)$ to retain both firms in the home country.

(ii) Medium value of d: $2/3 \leq d \leq 15/7$.

When d is in the range $(2/3, d^*]$, it follows from (iii) of Proposition 3 that the equilibrium location pattern changes from HH to HF as the relocation cost f decreases (i.e., globalization proceeds). When f falls below $\tilde{f}$ and if the welfare-maximizing tax, $\widetilde{t}_{HH}(d)$, were maintained, the firms would be induced to relocate abroad, which ends up lowering the welfare of country H to W_{HF}, as shown in Figure 4. Hence, as globalization proceeds, the government needs to lower the tax rate according to $t_{HH}(f)$ so as to retain both firms in country H. When the location cost falls below f_3, however, the location pattern that maximizes the welfare is HF as shown in Figure 4. Accordingly, the government should choose the tax rate that induces only one firm to relocate. Intuitively, when f is small, so does $t_{HH}(f)$; thus, the effect of tax revenue is small. In this case, the decreased environmental damage resulting from the relocation of one firm dominates the reduction in tax revenue and profits, which implies that $W_{HF} > W_{HH}$. When d lies in the range $(d^*, 5/4)$, on the other hand, it follows from (v) of Proposition 4 that the equilibrium location pattern FF appears during the transition from HH to HF as f decreases. Inspection of the right panels of Figures 4 and 5 reveal that for $2/3 < d < 5/4$, *the welfare decreases first, and then increases as f decreases*. This non-monotonic change in domestic welfare stems from the fact that the largest welfare function is changed from W_{HH} to either W_{FF} or W_{HF} as a result of the decrease in the emission tax rate caused by lower f. Hence, recalling that the welfare functions W_{HH} and W_{HF} reach the highest welfare level at different tax rates, the welfare levels *do not change monotonically* in response to the progress of globalization that accompanies the monotonic decreasing of the optimal emission tax rate.

It follows from (v) of Proposition 5 that when the damage coefficient d is relatively large and lies in the range $[5/4, 2]$, and the equilibrium location pattern changes from FF to HF as globalization proceeds, as shown in the upper panel of Figure 6. The environmental damage is too large to make W_{HH} the largest. When the tax rate is relatively small, the marginal production cost of a domestic firm is not so high. In this case, the benefit of a small tax on the consumer surplus and the profit in addition to the tax revenue dominates the environmental damage, which makes W_{HF} larger compared to W_{FF}. With increasing globalization, the government has to lower the tax rate so as to realize W_{HF}. As depicted in the upper panel of Figure 6, W_{HF} increases first and then decreases as globalization proceeds. This non-monotonic welfare change stems both from the switching of the largest welfare function that has a peak at different tax levels (i.e., W_{HF} and W_{FF}) and from the inverse U-shaped form of the function W_{HF}.

To sum up, for $2/3 \leq d \leq 15/7$, the effect of increased globalization on domestic welfare is not monotonically increasing; in other words, the increased degree of globalization may reduce domestic welfare.

(iii) Large value of d: $15/7 < d$.

When country H places great value on the environmental quality, W_{FF} is the largest for any f as depicted in Figure 7. Hence, the government will sufficiently raise the tax in order to realize the location FF. The locating of all polluting firms in the foreign country gives rise to the largest welfare level (i.e., W_{FF}), which is constant regardless of the degree of globalization.

6 Firms Locate Before Governments Set Taxes

Finally, in this section, we consider the case where the government cannot commit to an *ex ante* optimal emission tax, and is expected to set the *ex post* optimal tax after the location of the firms has been chosen. The outcome of the third stage is the same as that of the model presented in the previous section. In the second stage, the government of the home country H chooses the optimal emission tax rate by maximizing the following social welfare functions conditioned on the predetermined location choices of the firms:

$$\hat{W}_{HH}(t_{HH};d) \equiv \frac{2}{9}\left[-(1+d)t_{HH}^2 - (1-2d)At_{HH} + (2-d)A^2\right],$$
$$\hat{W}_{HF}(t_{HF};d) \equiv \frac{1}{18}\left[(6-d)A^2 - (6-4d)At_{HF} - (3+4d)t_{HF}^2\right],$$
$$\hat{W}_{FF}(t_{FF};d) \equiv \frac{2}{9}A^2,$$

where t_{ij} represents the optimal emission tax rate conditioned on the location choices of the firms when firm 1 has chosen to locate in country i, while firm 2 has chosen to locate in country j. Note that in the case of FF, since there is no polluting firm the home country H, no pollution is generated, and thus, the welfare $\hat{W}_{FF}$ does not depend on the tax rate. Hence, the government does not need to impose any emission tax. On the other hand, the government of country H always chooses the *second-best* emission tax rate that maximizes domestic welfare, that is, $\tilde{t}_{HH}(d)$ or $\tilde{t}_{HF}(d)$ in (10), given the realized location choices of the firms.[9] The corresponding profits of the firms are given by

$$\begin{aligned} \hat{\pi}_{HH}(d) &= \frac{1}{9}\left[A - \tilde{t}_{HH}(d)\right]^2, \ \hat{\pi}_{HF}(d) = \frac{1}{9}\left[A - 2\tilde{t}_{HF}(d)\right]^2 \\ \hat{\pi}_{FH}(d,f) &= \frac{1}{9}\left\{[A + \tilde{t}_{HF}(d)]^2 - f\right\} \quad \text{and } \pi_{FF}(d) = \frac{1}{9}A^2 - f. \quad (14) \end{aligned}$$

[9] Note that the government can at most achieve the *second-best* solution due to the presence of imperfect competition in the good market *even if the location of firms is exogenously fixed.*

By comparing among $\hat{\pi}_{HH}(d)$, $\hat{\pi}_{HF}(d)$, and $\hat{\pi}_{FH}(d, f)$ in (14), we can obtain the following proposition:[10]

Proposition 8 *Under Assumptions 1 and 2, the optimal emission tax rates and the location patterns of the firms are given by (i)–(iv):*

(i) If $0 \leq d \leq \sqrt{3}/2$, then $\tilde{t}_{HH}(d) = (2d-1)A/2(1+d)$ and both firms remain in the home country H independently of f.

(ii) If $\sqrt{3}/2 \leq d \leq 3/2$, then $\tilde{t}_{HF}(d) = (2d-3)A/(3+4d)$ for $f \in [0, G(d)]$ and $\tilde{t}_{HH}(d)$ for $f \in [G(d), A^2/9]$, where $G(d)$ represents a level of f that satisfies $\hat{\pi}_{FH}(d, f) = \hat{\pi}_{HH}(d)$. The location pattern of firms changes from HF to HH as globalization proceeds.

(iii) If $3/2 \leq d \leq d_{\max}$, then no emission tax is imposed for $f \in [0, M(d)]$, $\tilde{t}_{HF}(d)$ for $f \in [M(d), G(d)]$, and $\tilde{t}_{HH}(d)$ for $f \in [G(d), A^2/9]$, where $M(d)$ represents a level of f that satisfies $\hat{\pi}_{FH}(d, f) = \pi_{FF} \equiv (A^2/9) - f$ and $d_{\max}$ satisfies $\hat{\pi}_{FH}(d, A^2/9) = \hat{\pi}_{HH}(d)$. The location pattern of firms changes with f according to $FF \implies HF \implies HH$ as globalization proceeds.

(iv) If $d_{\max} \leq d$, then no emission tax is imposed for $f \in [0, M(d)]$ and $\tilde{t}_{HF}(d)$ for $f \in [M(d), A^2/9]$. The location pattern of firms changes from FF to HF as globalization proceeds.

Proposition 8 implies the following. First, as the severeness of environmental damages (i.e., d) becomes greater, the government has a stronger

[10] The detailed proofs of Proposition 8 are available from the corresponding author upon request.

incentive to drive the polluting firms out; hence, the location patterns HF and FF are more likely to emerge. Second, as globalization proceeds (i.e., f decreases), the firms are more likely to locate abroad. These two outcomes are quite intuitive. Moreover, since the location choices of the firms change from $HH \implies HF$ (or FH) to $\implies FF$ as globalization proceeds, the optimal emission tax rate is changed according to $\tilde{t}_{HH}(d) \implies \tilde{t}_{HF}(d)(=\tilde{t}_{FH}(d)) \implies$ *emission taxes are abolished*. That is, the optimal emission tax rate is (step-wise) decreasing as globalization proceeds. This also accords with our intuition. In short, the relation between the cost of relocation and the pattern of relocation choice is *monotonic*, unlike that in the previous model with precommitted optimal emission taxes. As a decrease in f makes the firms easier to relocate abroad, the government is forced to adopt less strict environmental policies (i.e., lower emission tax rates) so as to retain the firms in the home country. However, since very low emission tax levels caused by sufficiently low values of f leads to a small W_{HH} , the government no longer wants to retain both firms.

Since the government always chooses the *second-best* emission tax for the *unconstrained* welfare maximizing problem, the resulting welfare under ex post emission taxation is higher than that under precommitted emission taxation. Moreover, the chosen optimal emission tax rate tends to be higher under ex post taxation than under precommitted taxation. This is because under ex post tax policy, the government need not care about the threat of relocation of the firms and thus can choose the optimal (=second-best) tax rate of the *unconstrained* welfare maximizing problem. This result is clearly different from that of Ulph and Valentini (2001) in that stricter environmental policies *may* emerge under a precommitted policy regime. The reason for this difference is that in their model, there are two competing governments that strategically interact through environmental policies, resulting in the Nash equilibrium emission limit (or leading to a *race-to-the bottom game*), which may be below that under ex post emission taxes, while there is no such strategic interaction in the present model.

In the monopolistic model of Petrakis and Xepapadeas (2003), they find that under precommitted emission taxation, there is always a gain in terms of domestic welfare if the monopolist does not locate. However, this conclusion does not generally hold in the present model in which the larger the degree of environmental damage, or the smaller the size of relocation cost, the more likely that the domestic welfare is the largest when the firm relocates abroad. This is because in the model of Petrakis and Xepapadeas, the monopolist can make larger abatement efforts to avoid heavier tax burdens in anticipating higher ex-post emission tax rates in the second stage of the game. This response makes the welfare of the home country greater than that in the model with precommitted emission taxation.

7 Conclusions

We have shown that the optimal tax rate, the equilibrium location pattern, and the consequent domestic welfare crucially depend on the degree of damage from pollution generated by the firms and the size of relocation costs. A change in the degree of damage affects both the cost from environmental damage and the benefits from the profits of the firms and the consumer surplus through the price change, while a change in the cost of relocation affects the relocation choices of the duopolistic firms. *When the degree of damage* *is intermediate*, the asymmetric equilibrium location pattern can occur, that is, one firm relocates its plant abroad, while another firm remains in the home country even if the firms are identical *in all aspects* ex ante. More importantly, under precommitted emission taxes, the *non-monotonic* relation between domestic welfare and the cost of relocation (the degree of globalization) may emerge; particularly, less stringent environmental policies (which are possibly caused by the increased degree of globalization) may reduce domestic welfare. In other words, *the effect of increased globalization or weaker environmental policies on domestic welfare is not monotonically increasing,* while such a counterintuitive non-monotonic relation does not arise under ex ante (time-consistent) emission taxes.

In this study, we have not considered the sophisticated treatment of the distribution of profits, the existence of the good market in a foreign country, and the market size asymmetries between countries or cost heterogeneity among the firms. A more important extension of the present analysis is to introduce the strategic interaction between several competing governments through environmental policies. These extensions surely deserve further study.

Appendix

Lemma 1 *When $0 \leq d \leq 2/3$, W_{HH} is the largest for $t \in [0, A/2]$.*[11]*.*

Proof. It follows from (13) that $g_3(t; d) = 18(W_{HH} - W_{HF}) = 0$ has one negative root, t_3, and one positive root, $t_{6,}$ for $0 \leq d \leq 2/3$. Hence, $g_3(t; d) \geq$

[11] When the emission tax rate is negative, the equilibrium location is given by HH, irrespective of the value of f, which is drawn in Figure 1. To save space, we focus on the case where the tax rate is nonnegative in this appendix.

0 for $t \in [t_3, t_6]$, while it is negative for $t \notin [t_3, t_6]$. Moreover, it is easy to see that $0 < W_{FF} < W_{HF}\ (0; d) < W_{HH}(0; d)$ and that $W_{HF}(A/2; d) < W_{FF} < W_{HH}(A/2; d)$. Note also that $W_{HH}(t; d)$ is a concave function of t and W_{FF} is a constant function. Taken together, W_{HH} is the largest in $t \in [0, A/2]$. ■

Lemma 2 *When $2/3 < d \leq d^*$, W_{HF} is the largest for $t \in [0, t_3]$, while W_{HH} is the largest if $t \in [t_3, t_5]$.*

Proof. Differentiating W_{HH} and W_{HF} with respect to d yields

$$\frac{\partial W_{HH}(t; d)}{\partial d} = -\frac{2}{9}(t-A)^2 < 0 \text{ and } \frac{\partial W_{HF}(t; d)}{\partial d} = -\frac{1}{18}(A-2t)^2 < 0, \quad \text{(A.1)}$$

for $t < A/2$. This implies that the functions $W_{HH}(t; d)$ and $W_{HF}(t; d)$ are decreasing in d, while the function W_{FF} takes a constant value independently of d. Hence, when $d = d^*$, the functions $W_{HH}(t; d)$ and $W_{HF}(t; d)$ take a minimum value for each t. We compare the welfare functions at $d = d^*$. Since the quadratic equation $g_3(t; d^*) = 0$ has two positive real roots, $0 < t_3 < t_6$, for $2/3 \leq d$ and since the graph of $g_3(t; d^*)$ is inverse U-shaped in t, $g_3(t; d^*) \equiv 18\,[W_{HH}(t; d^*) - W_{HF}(t; d^*)] \leq 0$ for $t \in [0, t_3]$ implies that $W_{HF}(t; d^*) \geq W_{HH}(t; d^*)$ for $t \in [0, t_3]$. Next, we compare between $W_{HF}(t; d^*)$ and W_{FF}. When $t = 0$,

$$W_{HF}(0; d^*) = \frac{1}{18}\,(6 - d^*)\,A^2 > \frac{2}{9}A^2 = W_{FF},$$

where the inequality follows from the fact that $d^* < 15/7$, while $W_{HF}(t_3; d^*) = W_{FF}$ by definition of d^*. Taken together, it turns out that $W_{HF}(t; d)$ is the largest for $t \in [0, t_3]$.

Consider a case where $t \in [t_3, t_5]$. Since $g_3(t; d) \geq 0$ for $t \in [t_3, t_6]$ and since $t_5 < t_6$, $g_3(t;d) \geq 0$ for $t \in [t_3, t_5]$. This implies that $W_{HH} \geq W_{HF}$ for $t \in [t_3, t_5]$. In addition, for $d < d^*$, by definition of d^* $W_{FF} = W(t_2^*; d^*) < W_{HF}(t; d^*)$. Combining these facts, it turns out that $W_{HH}(t;d)$ is the largest for $t \in [t_3, t_5]$. ■

Lemma 3 *When $d^* \leq d < 5/4$, W_{HF} is the largest for $t \in [0, t_4]$, W_{FF} is the largest for $t \in [t_4, t_2]$, and W_{HH} is the largest for $t \in [t_2, t_6]$.*

Proof. For $t \in [0, t_4]$ $g_2(t;d) \leq 0$ implies $W_{FF} \leq W_{HF}$. Since $W_{HH}(t;d)$ and $W_{HF}(t;d)$ are decreasing functions of d, the intersection between the curves $W_{HH}(t;d)$ and $W_{HF}(t;d)$ is situated below the horizontal line W_{FF} for $d^* \leq d$. As shown in Figure 5, we have $t_4 < t_3 < t_2$. An inspection of Figure 5 delivers the desired result. ■

Lemma 4 *When $5/4 \leq d \leq 2$, W_{HF} is the largest for $t \in [0, t_4]$, while W_{FF} is the largest for $t \in [t_4, A^2/2]$. When $2 < d \leq 15/7$, W_{FF} is the largest for $t \in [0, t_1]$ or $t \in [t_4, A^2/2]$, while W_{HF} is the largest for $t \in [t_1, t_4]$.*

Proof. It follows from (11) that W_{HH} is never the largest since W_{HH} cannot intersect W_{FF} (recall that the quadratic equation $g_1(t;d) = 0$ has complex roots). Hence, we compare W_{HF} with W_{FF}. When $5/4 \leq d \leq 2$, $W_{HF}(t;d)$ is the largest for $t \in [0, t_4]$ because $g_2(t;d) \equiv 18 [W_{FF} - W_{HF}] \leq 0$ for $t \in [0, t_4]$, while W_{FF} is the largest for $t \in [t_4, A/2]$ because $g_2(t;d) \geq 0$ for $t \geq t_4$. When $2 < d \leq 15/7$, on the other hand, since $g_2(t;d) \leq 0$ for $t \in [0, t_1]$, W_{FF} is the largest for $t \in [0, t_1]$. The rest of the proof is the same as above. ■

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