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## Emission Taxes, Firm Relocation, and Quality Differences

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# Emission Taxes, Firm Relocation, and Quality Differences

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## Abstract

This paper studies the effect of an emission tax on the relocation decision in a duopoly with exogenous vertical product differentiation. We establish the relationship between quality difference, relocation cost, and marginal damage of emissions in a two-country-setting for three cases: An environmental tax set only by one country, non-cooperative environmental taxation in both countries, and coordinated environmental taxation. We consider two different timings: a time-consistent government, and a committed government. The higher the quality difference, the more likely it is that at least one firm relocates to the foreign country. A lower marginal damage decreases the equilibrium tax rate and lowers the incentive for relocation. If also the foreign country applies an emission tax, there is no equilibrium in which both firms relocate to the foreign country. If both governments set taxes non-cooperatively, the low-quality firm never relocates in equilibrium. If both countries set taxes cooperatively, it is more likely that both firms remain in the home country. Also, relocation of the low-quality firm only is a possible outcome of cooperative taxation.

JEL Classification: H23, F18, L13, Q58

Keywords: relocation, environmental policy, vertical quality differences, emission tax

## 1 Introduction

Environmental damage generated by firms' production has induced many governments to adopt environmental policy measures such as emission limits or emission taxes. These measures typically result in additional cost for firms. If firms have the choice to relocate

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production to another country, cost increases induced by environmental regulation may motivate firms to relocate to countries with less strict environmental regulation. If relocation of firms results in welfare losses to their home countries, the threat of relocation might, in turn, result in relaxed environmental regulation.

Although governments may refrain from imposing too strict environmental regulation given the threat of relocation, neither a race to the bottom is observable regarding environmental policy on a global level nor do all firms relocate to countries with lower environmental standards than those in their respective home countries. The reasons for firms (not) to relocate are manifold. A crucial factor in the relocation decision may be quality competition. A firm that offers a higher product quality typically faces a less elastic demand function than a firm that offers products of lower quality. Therefore, a high-quality firm is more capable of passing through the cost of environmental regulation than a low-quality firm. At the same time, higher profits stemming from higher product quality and relaxed competition may allow a firm to relocate to another country with less strict environmental policy at a fixed cost.

If asymmetric product quality results in asymmetric relocation incentives, environmental policy may also differ depending on the product quality provided by domestic firms. Therefore, this paper analyzes the interaction of environmental taxation and relocation decisions of firms when firms offer products of different quality levels.

While the analysis of relocation decisions as the result of environmental policy has received some attention in the literature, the consideration of product differentiation has only received little attention so far to the best of our knowledge (see Reinaud, 2008 for some basic intuitions).

Our analysis is related to the literature on the pollution haven hypothesis, which states that firms prefer to produce in countries with less stringent environmental standards as this allows them to produce at lower cost. As a result, governments might abstain from too strict environmental policy, resulting in a race to the bottom. This intuitive idea has been challenged by theoretical studies as well as by empirical findings (see Sturm, 2003; Rauscher, 2005 for surveys).

Markusen et al. (1996) develop a model with two regions and two firms. They show that optimal environmental policy in an open economy where firms decide on their location differs from the closed economy setting. In their setting, small changes in environmental policy may result in firm relocation and large changes in welfare. Motta & Thisse (1994) also show that strict environmental policy might result in a relocation of domestic firms. Rauscher (1995), however, shows that international tax competition for environmental taxes can result in tax rates that are either too low or too high from

a welfare perspective. A similar finding is presented by Hoel (1997), who shows that international competition on environmental policy may result in a stricter environmental regulation than international cooperation. Greaker (2003) also shows that the possibility of firms to relocate might result in stricter environmental regulation. Heuson (2010) discusses the implication of market power on the optimal choice of environmental policy instruments.

Empirically, evidence for the pollution haven hypothesis is mixed. Xing and Kolstad (2002) find that for heavily polluting industries such as chemicals and primary metals the laxity of environmental regulation is an important factor for FDI decisions, but is not significant for other industries. Cole and Elliott (2005) confirm the pollution haven hypothesis for FDI from the US to Brazil and Mexico for capital-intensive industries. Recently, Borghesi et al. (2016) have analyzed the effect of the EU-ETS on outward FDI with a special focus on Italian firms. While firms covered by the EU-ETS do not show a general tendency to relocate on average, firms exposed to international carbon leakage show such a tendency. Concerning the effect of environmental policy on foreign direct investment (FDI), Elliot and Zhou (2012) present a theoretical framework showing that more stringent environmental standards may increase in capital inflows. Dong et al. (2012) show that FDI decisions of firms may raise emission standards if market sizes of the two respective countries are small. But for large market sizes, FDI will not effect on emission standards of the "South".

The paper that is most closely related to our analysis is Ikefuji et al. (2016), who analyze the effect of environmental tax policy and relocation choices in a two county-setting. In their model, a market for the homogeneous output good exists only in one country. In this country, the government sets an environmental tax for production emissions. They find that the optimal emission tax in the home country is non-decreasing with the cost of relocation and that welfare varies in a non-monotonic way.

Our paper differs from Ikefuji et al. (2016) in two ways, marking our contribution to the literature. First, we include vertical product differentiation in our analysis, showing that it results in asymmetric incentives for firms to relocate. In addition, the welfare consequences of relocation differ, depending on which firm relocates. Second, we also analyze the effect on environmental taxation in the foreign country, studying both non-coordinated and coordinated taxation. The foreign government has an incentive to respond to environmental damages. We show that environmental taxation by the foreign government changes the relocation equilibria and equilibrium environmental policy.

Against this background, we analyze the effect of environmental policy on relocation decisions, when a duopolistic market is characterized by vertical quality differentiation.

We consider first a scenario where the government in the home country cannot commit to an environmental tax ex-ante and where it decides on taxation after the location choice by firms. We show that the incentive for the high-quality firm to relocate differs from the incentive of the low-quality firm. It is not only the environmental policy but also the competitive environment that is driven by quality differences that has an impact on relocation decisions. We show that quality differences between firms are an important parameter and that not all firms are equally likely to relocate in the face of environmental policy-induced cost. The higher the quality difference, the higher is the probability that at least one firm relocates to the foreign country. A Nash equilibrium in which both firms relocate to the foreign country only exists for a limited range of relocation cost and quality difference. Therefore, optimal environmental policy differs depending on the quality ranking provided by domestic and possibly foreign firms. If the home government commits to an environmental tax rate before firms decide whether to relocate, no equilibrium is feasible in which the high-quality firm remains in the home country, and the low-quality firm relocates. So relocation equilibria and environmental taxation are not only driven by quality differences, but also by the timing of decisions.

It is straightforward to assume that also the foreign government takes environmental damages and (re)location decisions of firms into account. Therefore, this paper takes environmental policy decisions of the foreign country into account and analyzes the interaction of the two governments. Our analysis shows that environmental taxation of the foreign country changes optimal relocation decisions of both firms when compared to unilateral environmental taxation. For instance, if both governments set environmental taxes non-cooperatively, there is no Nash equilibrium in which the low-quality firm relocates to the foreign country. Our results indicate that tax competition does not necessarily result in a race to the bottom in environmental taxation.

In addition, environmental taxes of both countries result in higher tax rates in the home country. If both governments set tax rates cooperatively, it is more likely that no firm relocates. In addition, under cooperative taxation also equilibria exist, in which the low-quality firm relocates.

The rest of the paper is organized as follows. In the next section, the basic model is presented. In section 3, we analyze the effect of a unilateral environmental tax on relocation decisions for both firms for a time-consistent government. Section 4 analyses the effect of alternative values in the damage function. Section 5 considers an alternative timing of the game, showing results for a committed government. Section 5 analyses non-cooperative and coordinated environmental tax setting in both countries. Section 7 concludes.

## 2 The Model

Consider two countries  $j = H, F$ . In country  $H$ , two firms  $i, i = 1, 2$  sell a product with different quality levels  $s_i$ . Assume without loss of generality that firm 1 is the high-quality firm, and firm 2 is the low-quality firm, i.e.  $s_1 > s_2$ . In what follows, we assume an exogenous quality ranking of  $s_1 = \lambda > s_2 = 1$ .

Firms sell their product only in  $H$ ; there is no product market in country  $F$ . This assumption allows us to focus on the firms' location decisions without considering the effects on consumer surplus in  $F$ .

Consumers are heterogeneous with respect to their preference for quality  $\theta$ , which is distributed uniformly on the interval  $[0,1]$ . The heterogeneity in preference parameter  $\theta$  may be interpreted as differences in income. Each consumer buys at most one unit of the most preferred good. The utility derived from no purchase is zero, while a consumer who buys one unit of the good obtains a net utility of

$$U = \theta s_i - p_i, \quad i = H, L. \quad (1)$$

The marginal consumer indifferent between purchasing the high-quality good (from firm 1) and the low-quality good (from firm 2) is given by  $\theta^* = \frac{p_1 - p_2}{\lambda - 1}$ , the marginal consumer indifferent between purchasing the low-quality good and not buying is given by  $\theta^{**} = p_2$ . Demand for both products is given as  $q_1 = 1 - \theta^*$  and  $q_2 = \theta^* - \theta^{**}$ . The market is not covered, which means that not all consumers necessarily buy a product. Consumers with a quality preference below  $\theta^{**}$  do not buy a good. The higher quality differentiation (and hence, market power), the larger is the share of consumers who do not buy a good. Therefore environmental policy and relocation decisions may result in quantity effects: If, e.g., environmental policy increases the equilibrium price  $p_2$ , then c.p. more consumers abstain from buying a product.

Assume that one unit of the product results in one unit of emissions of a local pollutant. Consider for the baseline scenario that emissions cause damage according to the damage function  $D = \frac{1}{2}q_i^2$ , where marginal damage is given by  $q_i$ . We will discuss the effect of a different damage function in section 4.

In the baseline scenario, the government in country  $H$  may levy an environmental tax  $\tau_H$  on the emissions generated in  $H^1$ . In section 5 we will allow also the government in  $F$  to impose an environmental tax  $\tau_F$  on the emissions generated in  $F$ .

Both firms are initially located in country  $H$  but may relocate to country  $F$  at fixed

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<sup>1</sup>Since one unit of output generates one unit of emissions, a tax on emissions is equivalent to a tax on output.

cost  $\phi$ . Therefore, a trade-off arises between bearing higher variable cost due to the environmental tax and relocating to  $F$  and not having to pay the environmental tax in  $H$ , but having to pay fixed cost of relocation  $\phi$ . Production technologies exhibit constant marginal costs, which are normalized to zero.

First, we analyze a scenario of a time consistent policy, where in the first stage firms decide whether to relocate to the foreign country or not. In the second stage, the government sets a welfare-maximizing tax rate, and in the third stage, firms compete in prices. We discuss an alternative timing, where the government commits to an environmental tax rate in section 5.

### 3 Time-Consistent Policy

In this section, we consider a scenario, where the government in  $H$  pursues a time-consistent strategy. We solve the game by backward induction.

#### 3.1 Price Competition

In the third stage of the game, firms compete in prices. The profit of each firm depends on its own location decision as well as on the location decision of its competitor. Therefore we consider all location equilibria that are possible from an ex-ante perspective: Both firms remain in country  $H$  (equilibrium  $HH$ ), the high-quality firm remains in  $H$ , the low-quality firm relocates to  $F$  (equilibrium  $HF$ ), the high-quality firm relocates to  $F$ , the low-quality firm remains in  $H$  (equilibrium  $FH$ ), and both firms relocate to  $F$  (equilibrium  $FF$ ). Let  $\Pi$  denote total profits and  $\pi$  operating profits (total profits net of relocation cost), with  $\Pi_1^{Hj} = \pi_1^{Hj}$ ,  $\Pi_2^{jH} = \pi_2^{jH}$  and  $\Pi_1^{Fj} = \pi_1^{Fj} - \phi$ ,  $\Pi_2^{jF} = \pi_2^{jF} - \phi$ . The following payoff matrix shows profits under the four possible strategy combinations.

1,2	$H$	$F$
$H$	$\Pi_1^{HH}, \Pi_2^{HH}$	$\Pi_1^{HF}, \Pi_2^{HF}$
$F$	$\Pi_1^{FH}, \Pi_2^{FH}$	$\Pi_1^{FF}, \Pi_2^{FF}$

Equilibrium prices, quantities, and profits for the four equilibria can be found in Appendix A.1.

If both firms remain in country  $H$  (equilibrium  $HH$ ), firms' profits are

$$\Pi_1^{HH} = (p_1^{HH} - \tau_H) q_1^{HH}, \Pi_2^{HH} = (p_2^{HH} - \tau_H) q_2^{HH}. \quad (2)$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), firms' profits are

$$\Pi_1^{HF} = (p_1^{HF} - \tau_H) q_1^{HF}, \Pi_2^{HF} = p_2^{HF} q_2^{HF} - \phi. \quad (3)$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), firms' profits are

$$\Pi_1^{FH} = p_1^{FH} q_1^{FH} - \phi, \Pi_2^{FH} = (p_2^{FH} - \tau_H) q_2^{FH}. \quad (4)$$

If both firms relocate to country  $F$  (equilibrium  $FF$ ), firms' profits are

$$\Pi_1^{FF} = p_1^{FF} q_1^{FF} - \phi, \Pi_2^{FF} = p_2^{FF} q_2^{FF} - \phi. \quad (5)$$

In the cases  $HH$ ,  $FH$ , and  $FF$ , the quantity of firm 1 exceeds the quantity of firm 2. Therefore, profit for firm 1 is higher than for firm 2. The difference of profits  $\Pi_1 - \Pi_2$  increases in  $\lambda$ . These findings also hold for location choices  $HF$  if the quality difference is sufficiently large. Therefore in this case, the environmental damage resulting from the high-quality firm if it produces in  $H$  exceeds the environmental damage of the low-quality firm if it produces in  $H$ . Also tax revenue collected from the high-quality firm in  $H$  exceeds tax revenue collected by the low-quality firm.

The quantity difference  $q_1 - q_2$  decreases in the degree of vertical product differentiation  $\lambda$ . Firm 1 charges a higher price ( $p_1 > p_2$ ), with the price difference  $p_1 - p_2$  increasing in the quality difference  $\lambda$ . Therefore, environmental damage and optimal environmental taxation also depend on quality differentiation.

### 3.2 Environmental Policy

Consider that in the second stage the government in country  $H$  taxes the output of each firm producing in  $H$ . The government sets a tax rate  $\tau_H$  to maximize social welfare, given as the sum of consumer surplus, firms' profits, tax revenue less the environmental damage.<sup>2</sup> The environmental tax has three effects: It increases prices, generates tax revenues, and may motivate one firm or both firms to relocate and thereby reduce emissions (and tax revenue) in the home country.

Total welfare in  $H$  and thus the welfare-maximizing choice of  $\tau_H$  depends on location

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<sup>2</sup>We assume that the government takes into account the profits of all firms that produce in its country. Thereby, we abstract from a situation where profits of a foreign firm are repatriated to the home country and are therefore part of the welfare in  $H$ .



decisions in the first stage of the game. Therefore, all relevant location combinations are considered in the following.

If both firms remain in country  $H$  (equilibrium  $HH$ ), welfare is given as

$$W_H^{HH} = CS_H^{HH} + \Pi_1^{HH} + \Pi_2^{HH} + \tau_H^{HH} (q_1^{HH} + q_2^{HH}) - \frac{1}{2} (q_1^{HH} + q_2^{HH})^2. \quad (6)$$

The resulting welfare maximizing tax rate is

$$\tau_H^{HH} = \frac{(2\lambda + 7)\lambda}{(\lambda + 1)(8\lambda + 1)}. \quad (7)$$

The equilibrium tax rate  $\tau_H^{HH}$  decreases in  $\lambda$ . Since both firms produce in  $H$ , all production emissions occur in  $H$ . A higher degree of product differentiation weakens price competition, increases prices and profits, lowers quantities and thereby lowers environmental damage. Therefore a lower tax rate is needed to correct the externality. As a result, the welfare-maximizing tax-rate is lower if products are more differentiated and competition is relaxed.

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), welfare is given as

$$W_H^{HF} = CS_H^{HF} + \Pi_1^{HF} + \tau_H (q_1^{HF}) - \frac{1}{2} (q_1^{HF})^2. \quad (8)$$

The welfare maximizing tax rate is

$$\tau_H^{HF} = \begin{cases} \frac{\lambda(\lambda-1)(9\lambda-4\lambda^2-3)}{-3\lambda-\lambda^2+4\lambda^3+1} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8} \end{cases}. \quad (9)$$

The welfare maximizing tax rate  $\tau_H^{HF}$  increases in  $\lambda$  for sufficiently low  $\lambda$  and decreases then. Given that only firm 1 produces in  $H$ , the production emissions of firm 2 generate no environmental damage in  $H$ . Therefore, the marginal damage of production is lower compared to  $HH$  and so is the optimal tax rate. If the quality difference is small, the optimal tax rate is also small, as a higher tax rate would drive the high-quality firm out of the market. An increase in the quality difference increases the ability of firm 1 to pass-through the tax rate because of less elastic demand. Therefore the optimal tax rate increases. If the quality difference is sufficiently large, the quantity of firm 1 is sufficiently low so that no tax is needed to correct the externality.

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ),

welfare is given as

$$W_H^{FH} = CS_H^{FH} + \Pi_2^{FH} + \tau_H (q_2^{FH}) - \frac{1}{2} (q_2^{FH})^2. \quad (10)$$

The welfare maximizing tax rate is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda-1)(4\lambda-2\lambda^2-1)}{\lambda(-9\lambda+8\lambda^2+2)} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}. \quad (11)$$

Again, part of the emission occur in  $F$ , but now it is the high-quality firm that produces abroad. As in the case  $HF$ , the welfare maximizing tax rate  $\tau_H^{FH}$  is hump-shaped but compared to location combination  $FH$ , the government has to take into account that it is the low-quality firm that produces at home. Demand for the low-quality firm is more elastic. Therefore, the optimal tax rate is lower. Also, the quality difference for which the optimal tax rate is zero is lower when compared to the location choices  $HF$ .

If both firms relocate to country  $F$  (equilibrium  $FF$ ), there is no tax base in country  $H$ .

Figure 1 shows optimal tax rates in equilibria  $HH$  (black line),  $HF$  (light gray), and  $FH$  (dark gray).

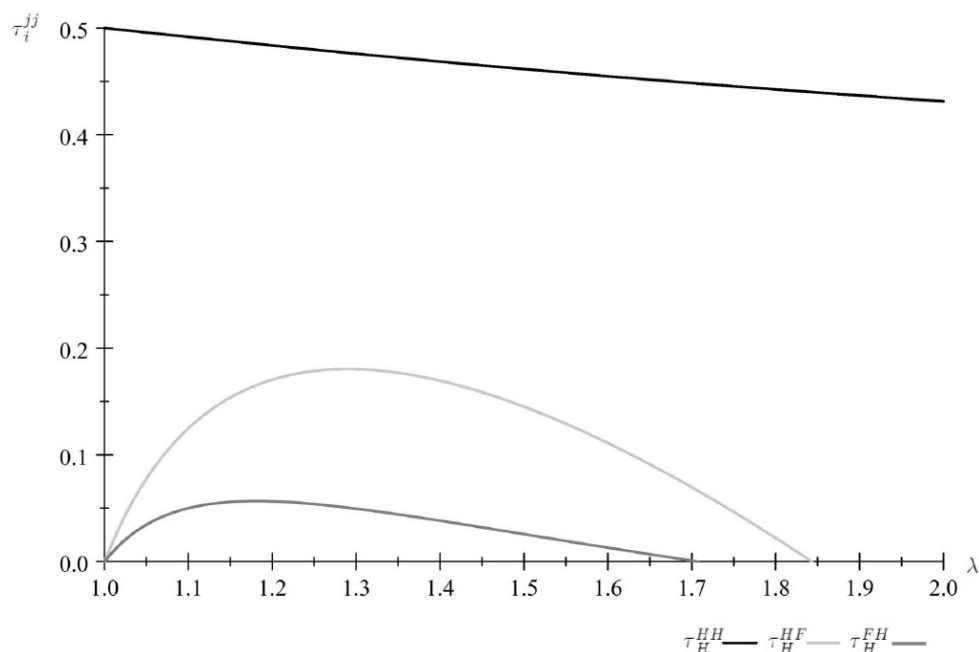


Figure 1: Tax rates  $\tau_H^{HH}$ ,  $\tau_H^{HF}$ , and  $\tau_H^{FH}$ .

Optimal tax rates depend on quality differences as well as on location decisions, with tax rates being the highest if no firm relocates.

An increase in product differentiation weakens competition and decreases quantities (and emissions). If both firms remain in  $H$ , the welfare maximizing tax rate decreases in  $\lambda$  because weakened competition decreases quantities and emissions. Relocation of at least one firm decreases emissions in  $H$  and decreases, therefore, the optimal tax rate. If one firm relocates to  $F$  and products are not sufficiently differentiated, a positive tax rate results in market exit of the remaining firm, because the environmental tax increases variable cost for the firm producing  $H$  and price competition is strong. The higher product differentiation is, the higher is the optimal tax rate because the taxed firm is more capable of passing through the environmental tax to consumers. If the product differentiation exceeds a threshold, the quantity decreases to a sufficient extent so that the optimal tax rate also decreases. For a high level of product differentiation, the quantity is sufficiently low, so that the optimal tax rate is zero.

Demand for the low-quality firm is more elastic than for the high-quality firm. Therefore optimal tax rates are always lower in the equilibrium  $FH$  than in  $HF$ .

Optimal emission taxation depends on the relocation decisions of firms which in turn depend on the quality difference and the cost of relocation.

### 3.3 Location Decision

In the first stage, firms decide whether or not to relocate to  $F$  based on expected profits, given the decision of the other firm. They anticipate the time-consistent government tax policy in the second stage. For each firm, the relocation decision is characterized by a trade-off whether to incur the variable cost of the tax levied on emissions or fixed cost of relocation and produce at zero marginal cost.

Both firms stay in  $H$  (equilibrium  $HH$ ) if  $\Pi_1^{HH} > \Pi_1^{FH} \wedge \Pi_2^{HH} > \Pi_2^{HF}$ , i.e.,  $\phi > \phi^{HH}$ . Firm 1 remains in  $H$ , but firm 2 relocates to  $F$  (equilibrium  $HF$ ) if  $\Pi_1^{HF} > \Pi_1^{FF} \wedge \Pi_2^{HF} > \Pi_2^{HH}$ , i.e.,  $\underline{\phi}^{HF} < \phi < \bar{\phi}^{HF}$ . Firm 1 relocates to  $F$  and firm 2 remains in  $H$  if  $\Pi_1^{FH} > \Pi_1^{HH} \wedge \Pi_2^{FH} > \Pi_2^{FF}$ , i.e.,  $\underline{\phi}^{FH} < \phi < \bar{\phi}^{FH}$ . Both firms relocate to  $F$  (equilibrium  $FF$ ) if  $\Pi_1^{FF} > \Pi_1^{HF} \wedge \Pi_2^{FF} > \Pi_2^{FH}$ , i.e.,  $\phi < \phi^{FF}$ . First stage equilibrium profits and cut-off values for  $\phi$  can be found in Appendix A.1. Figure 2 illustrates the resulting Nash equilibria depending on the quality difference  $\lambda$  and the cost of relocation  $\phi$ . We identify several combinations of  $\lambda$  and  $\phi$  with unique Nash equilibria  $HH$  (vertical dark gray stripes),  $FH$  (vertical light gray stripes),  $HF$  (horizontal light gray stripes),

and  $FF$  (horizontal dark gray stripes). In addition, there are regions with two Nash equilibria  $FH$  and  $HF$  (solid light gray) and a region with no Nash equilibrium in pure strategies (white area).

The quality difference  $\lambda$  is a key driver for the relocation decision. The lower the quality difference, the stronger is price competition between firms, resulting in lower prices, higher quantities, and lower profits. An increase in the quality difference  $\lambda$  weakens price competition and changes the result of the trade-off between paying the tax (variable cost) or paying the relocation costs (fixed cost). The higher the quality difference, the more likely it is that at least one firm relocates to country  $F$ . A higher quality difference weakens competition and reduces quantities. If relocation cost  $\phi$  is relatively high, it never pays off for any firm to relocate because the advantage of the lower variable cost is more than eaten up by the high fixed cost of relocation. Therefore,  $HH$  results as the equilibrium independent of  $\lambda$ . If relocation cost  $\phi$  is (close to) zero and the quality difference is sufficiently low, both firms produce large quantities so that it pays off for both firms to reduce variable cost at the expense of the fixed cost of relocation ( $FF$ ). As demand for the high-quality firm is less elastic than demand for the low-quality firm, relocating for a fixed cost and thereby reducing variable cost is more attractive for the low-quality firm than for the high-quality firm. Therefore, the low-quality firm has a stronger incentive to relocate for moderate values of  $\phi$  ( $HF$ ).

As the relocation decision creates a positive externality on the remaining firm in  $H$  by lowering the equilibrium tax rate, relocation of one firm dampens the relocation incentive for the remaining firm. As a result,  $HF$  as well as  $FH$  may be equilibria for some combinations of the quality difference and relocation cost. For some combinations of low levels of product differentiation and moderate relocation cost, no equilibrium exists. For each combination of location decisions, at least one firm has an incentive to deviate. For low levels of quality differentiation, price competition is strong. For intermediate values of relocation cost, it pays off for at least one firm to relocate. But the tax-dampening-effect of relocation of at least one firm counterbalances the advantage of relocating to  $F$ . Therefore, there is always the incentive to deviate from a given location combination for at least one firm, resulting in no equilibrium.

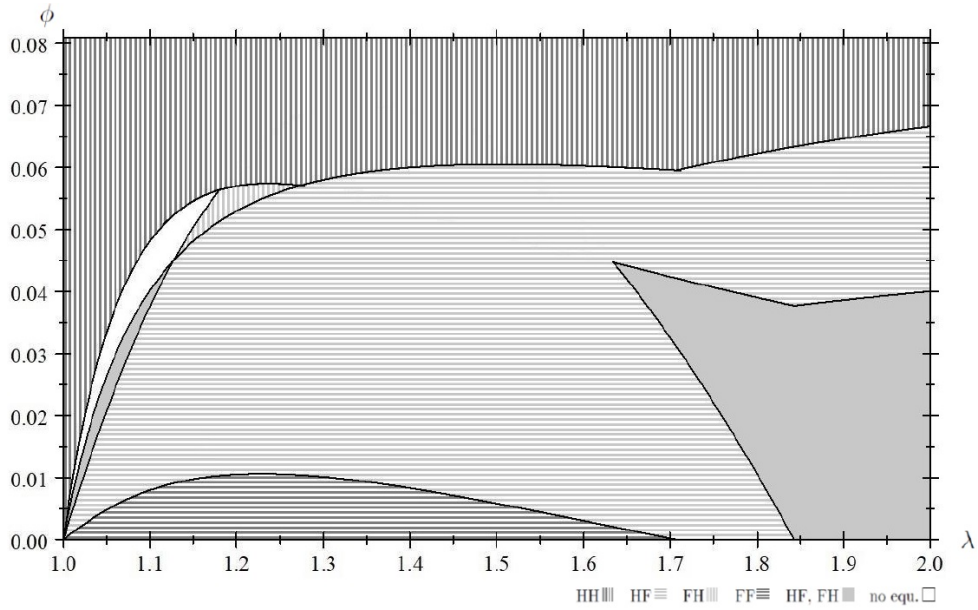


Figure 2: Location equilibria, unilateral taxation.

## 4 The Role of Marginal Damage

So far, we have considered a damage function  $D = \frac{1}{2}q_i^2$  for a baseline case. In this section, we explore the effect of different marginal damage parameters. For the purpose of clarity, we restrict our analysis to the comparison of the baseline scenario to one damage function with lower marginal damage ( $D = \frac{1}{4}q_i^2$ ) and another damage function with higher marginal damage ( $D = \frac{3}{4}q_i^2$ ).

### 4.1 Lower Marginal Damage

Consider first the damage function  $D = \frac{1}{4}q_i^2$ . This implies that the marginal damage of emissions is lower than that in the baseline scenario.

#### 4.1.1 Price Competition

The third stage of the game, where firms compete in prices, is identical to our analysis in section 3.

#### 4.1.2 Environmental Policy

In the second stage, the government in  $H$  maximizes social welfare taking into account the location decisions of the firms in the first stage. Equilibrium tax rates can be found

in Appendix A.2.

If both firms remain in  $H$  (equilibrium  $HH$ ), social welfare is

$$W_H^{HH} = CS_H^{HH} + \Pi_1^{HH} + \Pi_2^{HH} + \tau_H (q_1^{HH} + q_2^{HH}) - \frac{1}{4} (q_1^{HH} + q_2^{HH})^2. \quad (12)$$

The welfare-maximizing tax rate  $\tau_H^{HH}$  is

$$\tau_H^{HH} = \begin{cases} \frac{\lambda(11-2\lambda)}{12\lambda^2+14\lambda+1} & \text{if } \lambda < \frac{11}{2} \\ 0 & \text{if } \lambda \geq \frac{11}{2}. \end{cases}$$

If the quality difference is sufficiently large, it is optimal for the government in  $H$  not to tax the firms. The lower quantity resulting from product differentiation makes the environmental tax obsolete. An environmental tax would reduce quantity and environmental damage but the marginal loss in profit and consumer surplus would outweigh the marginal welfare gain from reduced pollution.

If the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  (equilibrium  $HF$ ), social welfare is

$$W_H^{HF} = CS_H^{HF} + \Pi_1^{HF} + \tau_H (q_1^{HF}) - \frac{1}{4} (q_1^{HF})^2. \quad (13)$$

The resulting welfare-maximizing tax rate  $\tau_H^{HF}$  is

$$\tau_H^{HF} = \begin{cases} \frac{2\lambda(1-\lambda)(4\lambda^2-7\lambda+2)}{8\lambda^3-6\lambda^2-2\lambda+1} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8}. \end{cases} \quad (14)$$

Again, the optimal tax rate is zero if the quality difference is sufficiently large.

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), social welfare is

$$W_H^{FH} = CS_H^{FH} + \Pi_2^{FH} + \tau_H (q_2^{FH}) - \frac{1}{4} (q_2^{FH})^2. \quad (15)$$

The welfare-maximizing tax rate  $\tau_H^{FH}$  is

$$\tau_H^{FH} = \begin{cases} \frac{(1-\lambda)(6\lambda^2-9\lambda+2)}{\lambda(12\lambda^2-14\lambda+3)} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4}. \end{cases}$$

The lower marginal damage of pollution results in lower optimal tax rates when compared to the baseline scenario.

If both firms relocate to country  $F$ , there is no tax rate in country  $H$ .

### 4.1.3 Location Decision

Similar to our analysis in section 3, in the first stage, both firms decide whether or not to relocate by comparing equilibrium profits depending on location decisions.

First stage equilibrium profits and cut-off values for  $\phi$  can be found in Appendix A.2.

Figure 3 illustrates the resulting Nash equilibria depending on the quality difference  $\lambda$  and the cost of relocation  $\phi$  for this damage function.

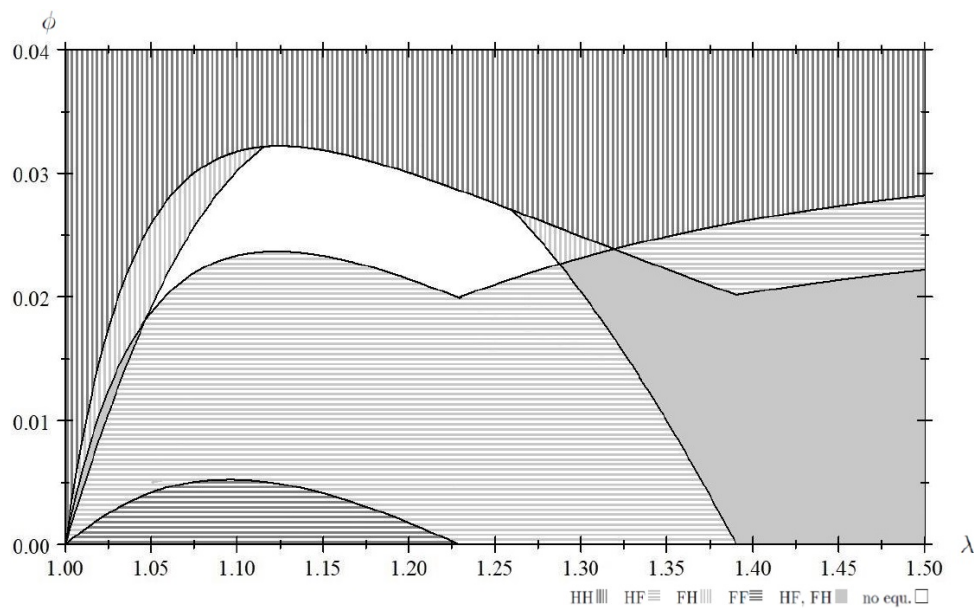


Figure 3: Location equilibria, unilateral taxation,  $D = \frac{1}{4}q^2$ .

Similar to section 3, we identify several combinations of  $\lambda$  and  $\phi$  with unique Nash equilibria  $HH$  (vertical dark gray stripes),  $FH$  (vertical light gray stripes),  $HF$  (horizontal light gray stripes), and  $FF$  (horizontal dark gray stripes). In addition, there are regions with two Nash equilibria  $FH$  and  $HF$  (solid light gray), and a region with no Nash equilibrium in pure strategies (white area).

Compared to the baseline case, the lower parameter value in the damage function does not change the existence and location of the location equilibria drastically. The lower marginal damage results in lower optimal tax rates. Therefore the trade off between variable cost (the tax rate) and relocation cost changes. Given the lower tax rates, the

incentive for relocation is weaker when compared to our baseline case. The area of the  $HH$ -equilibrium has increased (note the different scaling of the axes). In addition, the area of the  $FF$ -equilibrium is smaller, because a lower damage of emissions makes it less beneficial for the government in  $H$  that both firms relocate to  $F$ . Therefore, optimal tax rates are lower resulting in lower incentives for both firms to relocate. If only the low-quality firm relocates to  $F$ , the remaining environmental damage is lower when compared to the baseline case and so is the tax rate. Therefore the area where  $HF$  is an equilibrium has increased. Also, the area, in which no equilibrium exists, has increased. The lower tax rate compared to the baseline scenario combined with the tax-dampening effect of relocation increases the incentive for at least one firm to deviate for each combination of location decisions.

## 4.2 Higher Marginal Damage

Consider now the damage function  $D = \frac{3}{4}q_i^2$ . This implies that the marginal damage of emissions is higher than that in the baseline scenario.

### 4.2.1 Price Competition

The third stage of the game, where firms compete in prices, is identical to our description in section 3.

### 4.2.2 Environmental Policy

In the second stage, the government in  $H$  maximizes social welfare given the relocation decisions of both firms in the first stage. Equilibrium tax rates can be found in Appendix A.3.

If both firms remain in  $H$  (equilibrium  $HH$ ), social welfare is

$$W_H^{HH} = CS_H^{HH} + \Pi_1^{HH} + \Pi_2^{HH} + \tau_H (q_1^{HH} + q_2^{HH}) - \frac{3}{4} (q_1^{HH} + q_2^{HH})^2. \quad (16)$$

The welfare-maximizing tax rate is

$$\tau_H^{HH} = \frac{1}{2}.$$

With this tax rate, the low-quality firm exits the market, and the high-quality firm becomes a monopolist.



If the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  (equilibrium  $HF$ ), social welfare is

$$W_H^{HF} = CS_H^{HF} + \Pi_1^{HF} + \tau_H (q_1^{HF}) - \frac{3}{4} (q_1^{HF})^2. \quad (17)$$

The resulting tax rate  $\tau_H^{HF}$  is

$$\tau_H^{HF} = \begin{cases} \frac{2\lambda(\lambda-1)(-4\lambda^2+11\lambda-4)}{(4\lambda-3)(2\lambda^2+2\lambda-1)} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8}. \end{cases} \quad (18)$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), social welfare is

$$W_H^{FH} = CS_H^{FH} + \Pi_2^{FH} + \tau_H (q_2^{FH}) - \frac{1}{4} (q_2^{FH})^2. \quad (19)$$

The welfare-maximizing tax rate  $\tau_H^{FH}$  is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda-1)(-2\lambda^2+7\lambda-2)}{\lambda(-22\lambda+20\lambda^2+5)} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}. \end{cases} \quad (20)$$

Again, the optimal tax rate is zero if quality differentiation is sufficiently large. Compared to the baseline scenario and the scenario with lower marginal damage, the optimal tax rate is zero for a higher degree of quality differentiation. The quantity reducing effect of product differentiation has to be larger to make environmental taxation obsolete if the marginal damage of pollution is higher.

Tax rates are higher than those in the baseline scenario and the scenario with lower marginal damage.

If both firms relocate to  $F$  (equilibrium  $FF$ ), there is no tax rate in country  $H$ .

### 4.2.3 Location Decision

In the first stage, both firms decide whether or not to relocate by comparing equilibrium profits depending on location decisions.

First stage equilibrium profits and cut-off values for  $\phi$  can be found in Appendix A.3.

Figure 4 illustrates the resulting Nash equilibria depending on the quality difference  $\lambda$  and the cost of relocation  $\phi$  for this damage function.

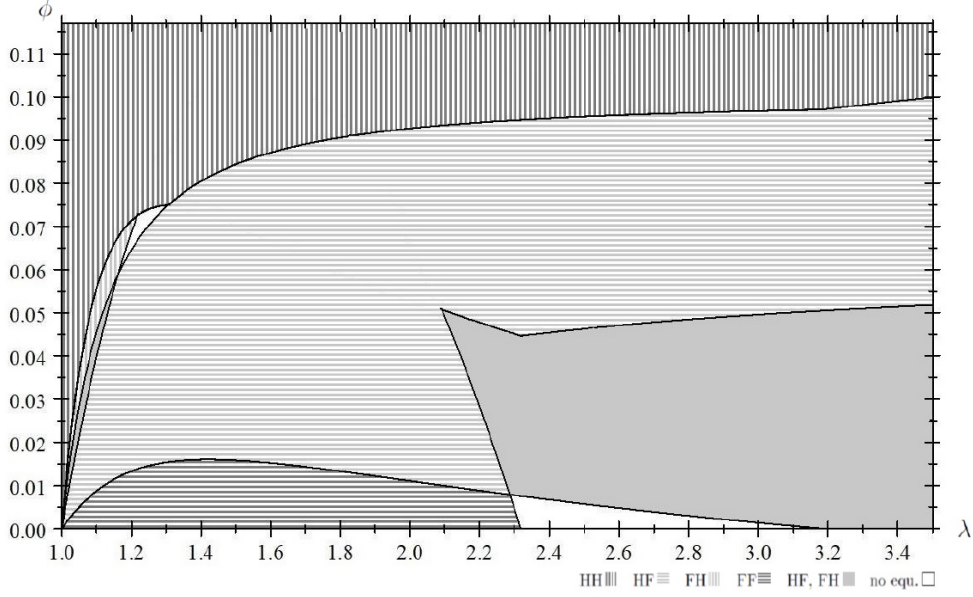


Figure 4: Location equilibria, unilateral taxation,  $D = \frac{3}{4}q^2$ .

Similar to Figure 2 and Figure 3 we identify several combinations of  $\lambda$  and  $\phi$  with unique Nash equilibria  $HH$  (vertical dark gray stripes),  $FH$  (vertical light gray stripes),  $HF$  (horizontal light gray stripes), and  $FF$  (horizontal dark gray stripes). In addition, there are regions with two Nash equilibria  $FH$  and  $HF$  (solid light gray), and a region with no Nash equilibrium in pure strategies (white area).

Again, the overall pattern of the equilibria is similar to the baseline case. Given the higher tax rates, the area where no Nash equilibrium exists is smaller when compared to the baseline case. The area of the  $HH$ -equilibrium is smaller compared to the baseline case (note again the different scaling of the axes). The higher marginal damage of emissions results in higher tax rates. Therefore the trade off between variable cost (the tax rate) and the fixed cost of relocation changes. Compared to the baseline case, the incentive for relocation is higher. This explains the increase in the area of the  $FF$ -equilibrium.

For all three damage functions considered, a higher value for  $\lambda$  increases the probability that at least one firm relocates, given the optimal emission taxes set by the government in  $H$ . A higher quality difference weakens competition between firms and reduces quantities. In cases where relocation cost is sufficiently low, it pays off for at least one firm to trade fixed cost of relocation for a lower variable cost. A change in marginal damage, as shown for  $D = \frac{1}{4}q_i^2$  and  $D = \frac{3}{4}q_i^2$ , affects location equilibria, but does not change the overall pattern of equilibria.

## 5 Environmental Taxes in Both Countries

So far, we have considered the case where an environmental tax is applied only in  $H$ . The government in  $F$  was assumed to be passive. This is in line with the analysis of Ikefuji et al. (2016). While this approach allows us to analyze the interaction of environmental damage, quality differences, and relocation cost, it is straightforward to assume that also the government in  $F$  applies an environmental tax. The relocation of at least one firm to  $F$  results in harmful emissions in  $F$ . From the perspective of  $F$ , environmental taxation on emissions in  $H$  increases emissions in  $F$  if relocation occurs. So relocation does not only change optimal environmental taxation in  $H$  but also in  $F$ . Therefore, in this section, we take environmental policy in  $F$  into account. We still abstract from consumers in  $F$  and assume that an output market exists only in  $H$ . With respect to the damage function, we assume the damage function parameter of the baseline case in both countries and further assume that there is no damage spillover.

### 5.1 Non-Cooperative Taxation

Assume that the governments in  $H$  and  $F$  set environmental taxes non-cooperatively. Hosting a firm results in profits and potential tax revenues on the one hand and harmful emissions on the other hand. The relocation trade-off for firms has now changed because relocation does not imply not being taxed.

#### 5.1.1 Price Competition

In the third stage, firms compete in prices. Equilibrium prices, quantities, and profits for the four equilibria can be found in Appendix A.4.

If both firms remain in country  $H$  (equilibrium  $HH$ ), firms' profits are

$$\Pi_1^{HH} = (p_1^{HH} - \tau_H) q_1^{HH}, \Pi_2^{HH} = (p_2^{HH} - \tau_H) q_2^{HH}. \quad (21)$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), firms' profits are

$$\Pi_1^{HF} = (p_1^{HF} - \tau_H) q_1^{HF}, \Pi_2^{HF} = (p_2^{HF} - \tau_F) q_2^{HF} - \phi. \quad (22)$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ),

firms' profits are

$$\Pi_1^{FH} = (p_1^{FH} - \tau_F) q_1^{FH} - \phi, \Pi_2^{FH} = (p_2^{FH} - \tau_H) q_2^{FH}. \quad (23)$$

If both firms relocate to country  $F$  (equilibrium  $FF$ ), firms' profits are

$$\Pi_1^{FH} = (p_1^{FH} - \tau_F) q_1^{FH} - \phi, \Pi_2^{FH} = (p_2^{FH} - \tau_H) q_2^{FH}. \quad (24)$$

### 5.1.2 Environmental Policy

Consider first that in the second stage governments set tax rates non-cooperatively. Equilibrium tax rates can be found in Appendix A.4.

If both firms remain in country  $H$  (equilibrium  $HH$ ), welfare is given as

$$W_H^{HH} = CS_H^{HH} + \Pi_1^{HH} + \Pi_2^{HH} + \tau_H^{HH} (q_1^{HH} + q_2^{HH}) - \frac{1}{2} (q_1^{HH} + q_2^{HH})^2. \quad (25)$$

The welfare maximizing tax rate is

$$\tau_H^{HH,NC} = \frac{(2\lambda + 7)\lambda}{(\lambda + 1)(8\lambda + 1)}, \quad (26)$$

which is the same as in the unilateral case (there is no tax base in country  $F$ ).

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), welfare in country  $H$  is given as

$$W_H^{HF} = CS_H^{HF} + \Pi_1^{HF} + \tau_H (q_1^{HF}) - \frac{1}{2} (q_1^{HF})^2 \quad (27)$$

and welfare in country  $F$  is given as

$$W_F^{HF} = \Pi_2^{HF} + \tau_F (q_2^{HF}) - \frac{1}{2} (q_2^{HF})^2. \quad (28)$$

The welfare maximizing tax rates  $\tau_H^{HF,NC}$  and  $\tau_F^{HF,NC}$  are

$$\tau_H^{HF,NC} = \begin{cases} \frac{-6\lambda^3 + 17\lambda^2 - 11\lambda + 1}{\lambda + 6\lambda^2 - 4} & \text{if } \lambda < 1.9267 \\ 0 & \text{if } \lambda \geq 1.9267 \end{cases} \quad (29)$$

$$\tau_F^{HF,NC} = \begin{cases} \frac{2\lambda^2 - 1}{6\lambda^3 + \lambda^2 - 4\lambda} & \text{if } \lambda < 1.9267 \\ \frac{(2\lambda^2 - 1)(\lambda - 1)}{\lambda(2\lambda - 1)(6\lambda - 5)} & \text{if } \lambda \geq 1.9267 \end{cases}.$$

Compared to our baseline case in section 3, the equilibrium tax rate in  $H$  is now higher.

This is the result of positive tax rate in  $F$ . If production of firm 2 is taxed, quantities and therefore emissions shift from country  $F$  to country  $H$ . As a result,  $H$  applies a higher equilibrium tax to correct the externality.

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), welfare in country  $H$  is given as

$$W_H^{FH,NC} = CS_H^{FH,NC} + \Pi_2^{FH,NC} + \tau_H \left( q_2^{FH,NC} \right) - \frac{1}{2} \left( q_2^{FH,NC} \right)^2. \quad (30)$$

Welfare in country  $F$  is given as

$$W_F^{FH,NC} = \Pi_1^{FH,NC} + \tau_F \left( q_1^{FH,NC} \right) - \frac{1}{2} \left( q_1^{FH,NC} \right)^2. \quad (31)$$

The welfare maximizing tax rates  $\tau_H^{FH, NC}$  and  $\tau_F^{FH, NC}$

$$\tau_H^{FH,NC} = \begin{cases} \frac{(2\lambda^3 - 6\lambda^2 + 2\lambda + 1)}{-8\lambda^3 + 3\lambda^2 + 2\lambda} & \text{if } \lambda < 2.5257 \\ 0 & \text{if } \lambda \geq 2.5257 \end{cases}$$

$$\tau_F^{FH,NC} = \begin{cases} \frac{(6\lambda^2 - 7\lambda + 2)}{8\lambda^2 - 3\lambda - 2} & \text{if } \lambda < 2.5257 \\ \frac{(6\lambda^3 - 10\lambda^2 + 4\lambda)}{8\lambda^3 - 8\lambda^2 + 1} & \text{if } \lambda \geq 2.5257 \end{cases}.$$

Again, equilibrium tax rates in  $H$  exceed equilibrium tax rates studied in section 3 (with  $F$  assumed to be passive). The intuition is similar to the case  $HF$ . Compared to a passive government in  $F$ , taxation in  $F$  shifts emissions to  $H$ , resulting in higher taxes. In addition, taxation in  $F$  dampens the relocation incentive stemming from taxation in  $H$ , as firms now anticipate that emissions will also be taxed in  $F$ .

If both firms relocate to country  $F$  (equilibrium  $FF$ ), welfare in country  $F$  is given as

$$W_F^{FF,NC} = \Pi_1^{FF,NC} + \Pi_2^{FF,NC} + \tau_F \left( q_1^{FF,NC} + q_2^{FF,NC} \right) - \frac{1}{2} \left( q_1^{FF,NC} + q_2^{FF,NC} \right)^2. \quad (32)$$

The welfare maximizing tax rate  $\tau_F^{FF, NC}$  is

$$\tau_F^{FF,NC} = \frac{2\lambda(5\lambda + 4)}{12\lambda^2 + 14\lambda + 1}.$$

Note that the taxation decisions of  $H$  and  $F$  are similar if both firms produce in

the respective country. But since there is no output market in  $F$ , there is no consumer surplus in  $F$  that has to be taken into account by the government.

### 5.1.3 Location Decision

In the first stage, both firms decide whether or not to relocate by comparing equilibrium profits depending on location decisions.

First stage equilibrium profits and cut-off values for  $\phi$  can be found in Appendix A.4.

Figure 5 illustrates the resulting Nash equilibria depending on the quality difference  $\lambda$  and the cost of relocation  $\phi$  for non-cooperative taxation in both countries.

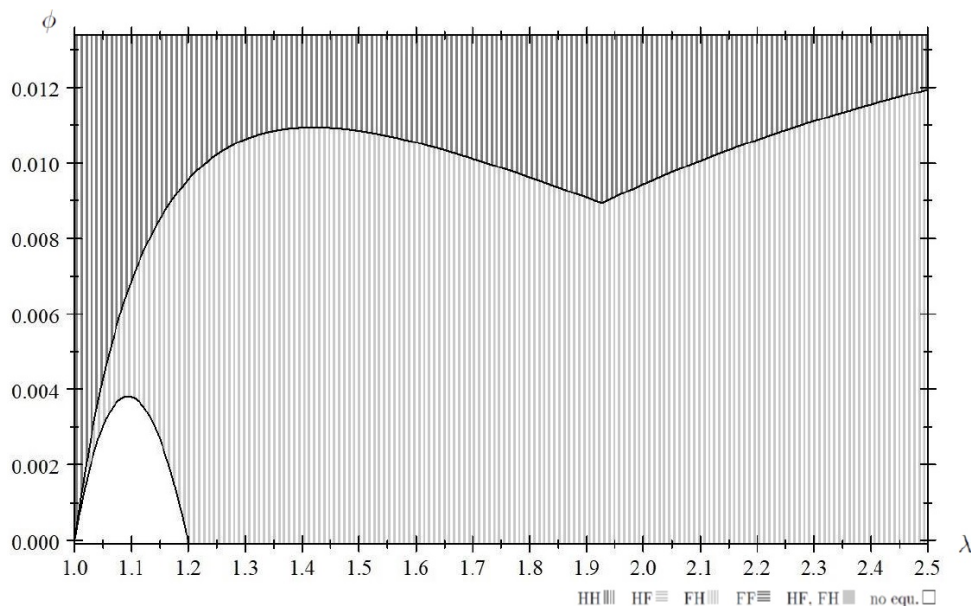


Figure 5: Location equilibria, bilateral, non-cooperative taxation.

If both governments apply an environmental tax, we identify several combinations of  $\lambda$  and  $\phi$  with unique Nash equilibria  $HH$  (vertical dark gray stripes) and  $FH$  (vertical light gray stripes), and a region with no Nash equilibrium in pure strategies (white area). There is no  $FF$ -equilibrium, no  $HF$ -equilibrium, and no area characterized by multiple equilibria. For low values of  $\lambda$ , there is an area, where no equilibrium exists.

Similar to Figure 2, there is an area of prohibitively high relocation cost so that no firm relocates ( $HH$ ). But compared to Figure 2, the critical relocation cost that results in the  $HH$ -equilibrium is much lower. As a result of  $F$  also taxing emissions, the difference in variable cost in case of relocation decreases. Therefore, for a given quality difference, the critical relocation cost, which prevents relocation of any firm, is lower.

There is no  $HF$ -equilibrium. If a firm relocates under uncoordinated taxation of both countries, it is always the high-quality firm that relocates. For a given quality difference, the cut-off value of relocation cost for which the high-quality firm relocates at the margin (given that the low-quality firm stays at  $H$ ) is higher than the cut-off value for the low-quality firm. Because of its higher profit, the high-quality firm is more inclined to relocate to the foreign country for a fixed cost than the low-quality firm. Therefore, it relocates for a higher fixed cost than the low-quality firm. The low-quality firm, in contrast, never has an incentive to relocate in equilibrium. Given that one firm (the high-quality firm) has relocated to  $F$ , country  $F$  has no incentive to attract the second firm as well.

## 5.2 Cooperative Taxation

Consider a scenario where the governments in  $H$  and  $F$  set environmental taxes cooperatively to maximize joint welfare. Coordination of environmental taxes internalizes the externality between governments in tax-setting.

### 5.2.1 Price Competition

The third stage of the game, where firms compete in prices, is identical to our description in section 5.

### 5.2.2 Environmental Policy

Consider first the case where in the second stage governments set tax rates non-cooperatively. Equilibrium tax rates can be found in Appendix A.5.

If both firms remain in  $H$ , welfare and the optimal tax rate is identical to the case  $HH$  under non-cooperative taxation.

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), global welfare is given as

$$W^{HF,C} = CS_H^{HF,C} + \Pi_1^{HF,C} + \Pi_2^{HF,C} + \tau_H \left( q_1^{HF,C} \right) + \tau_F \left( q_2^{HF,C} \right) - \frac{1}{2} \left( q_1^{HF,C} \right)^2 - \frac{1}{2} \left( q_2^{HF,C} \right)^2. \quad (33)$$

The welfare maximizing tax rates  $\tau_H^{HF,C}$  and  $\tau_F^{HF,C}$  are

$$\begin{aligned}\tau_H^{HF,C} &= \begin{cases} \frac{(\lambda-2)(1-2\lambda)}{2\lambda+1} & \text{if } \lambda < 2 \\ 0 & \text{if } \lambda \geq 2 \end{cases} \\ \tau_F^{HF,C} &= \begin{cases} \frac{1}{\lambda(2\lambda+1)} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(-2\lambda+2\lambda^2-1)}{\lambda(-11\lambda+8\lambda^2+5)} & \text{if } \lambda \geq 2 \end{cases} .\end{aligned}$$

Under cooperative taxation, the government in  $H$  sets a tax rate of zero, if quality differentiation is sufficiently large ( $\lambda \geq 2$ ). The government in  $F$  always sets positive tax rates.

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), global welfare is given as

$$W_H^{FH,C} = CS_H^{FH,C} + \Pi_1^{FH,C} + \Pi_2^{FH,C} + \tau_H(q_2^{FH,C}) + \tau_F(q_1^{FH,C}) - \frac{1}{2}(q_2^{FH,C})^2 - \frac{1}{2}(q_1^{FH,C})^2 . \quad (34)$$

Welfare in country  $F$  is given as

$$W_F^{FH,C} = \Pi_1^{FH,C} + \tau_F(q_1^{FH,C}) - \frac{1}{2}(q_1^{FH,C})^2 . \quad (35)$$

The welfare maximizing tax rates  $\tau_H^{FH,C}$  and  $\tau_F^{FH,C}$  are

$$\begin{aligned}\tau_H^{FH,C} &= \begin{cases} \frac{1}{\lambda(2\lambda+1)} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(-2\lambda+2\lambda^2-1)}{\lambda(-11\lambda+8\lambda^2+5)} & \text{if } \lambda \geq 2 \end{cases} \\ \tau_F^{FH,C} &= \begin{cases} \frac{(2\lambda-1)(2-\lambda)}{2\lambda+1} & \text{if } \lambda < 2 \\ 0 & \text{if } \lambda \geq 2 \end{cases} .\end{aligned} \quad (36)$$

Tax rates of  $H$  in equilibrium  $FH$  are identical to tax rates of  $F$  in equilibrium  $HF$ . Tax rates of  $H$  in equilibrium  $HF$  are identical to tax rates of  $F$  in equilibrium  $FH$ . This is, if each country hosts a firm under cooperation, tax rates in both countries depend only on the relative quality position of the respective domestic firm. If the quality difference is sufficiently high ( $\lambda \geq 2$ ), the optimal tax rate is zero in both cases for the country that hosts the high-quality firm 1. If the quality difference is below this threshold level, a positive tax rate is applied.



If both firms relocate to country  $F$  (equilibrium  $FF$ ), global welfare is given as

$$W^{FF,C} = CS_H^{FF,C} + \Pi_1^{FF,C} + \Pi_2^{FF,C} + \tau_F (q_1^{FF,C} + q_2^{FF,C}) - \frac{1}{2} (q_1^{FF,C})^2 - \frac{1}{2} (q_2^{FF,C})^2. \quad (37)$$

The welfare maximizing tax rate  $\tau_F^{FF,C}$  is

$$\tau_F^{FF,C} = \frac{2\lambda(5\lambda + 4)}{12\lambda^2 + 14\lambda + 1}.$$

Figures 6 and 7 show tax rates for unilateral, non-cooperative bilateral and coordinated bilateral taxation for equilibria in that one firm relocates (equilibria  $HF$  and  $FH$ ).

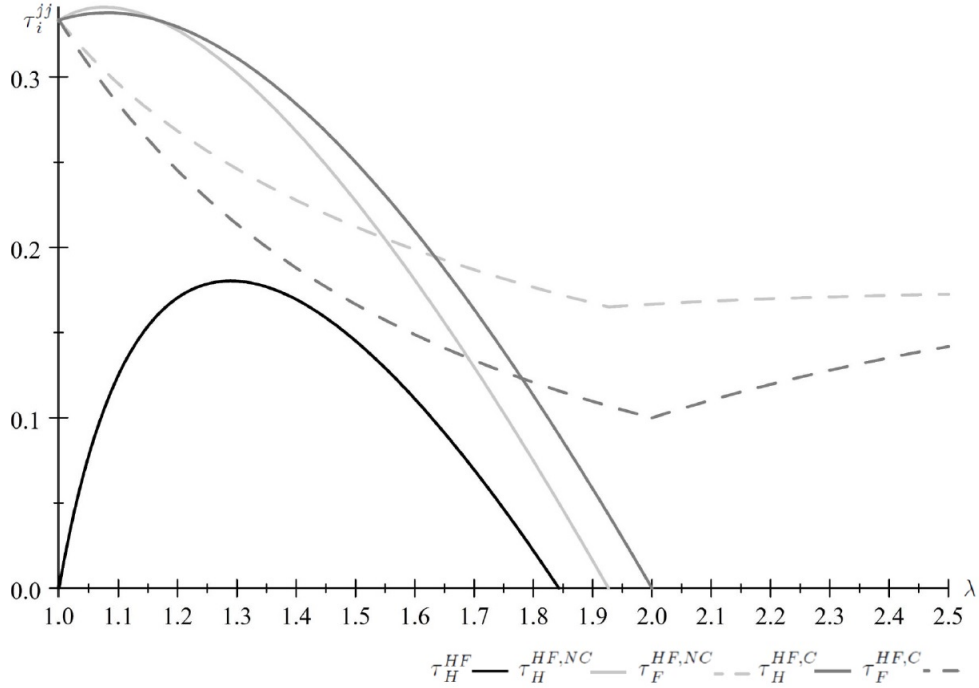


Figure 6:  $\tau_i^{jj}$  for unilateral, non-cooperative bilateral and coordinated bilateral taxation for  $HF$ .

In the location equilibrium  $HF$ , the tax rate in  $H$  in the case of no taxation in  $F$  is hump-shaped (see Figure 1 and section 3.2). If also country  $F$  taxes emissions, welfare-maximizing tax rates in  $H$  are higher than under no taxation in  $F$  because the competitive disadvantage of taxation in  $H$  is mitigated by positive tax rates in  $F$ . Tax

rates in  $H$  are again hump-shaped, but optimal tax rates are now positive even in the case of no product differentiation. If tax rates are set non-cooperatively, optimal tax rates are higher than those under cooperation for sufficiently large quality differences. The reason is that governments internalize the externality created by domestic taxation and reduce absolute quantities cooperatively. For low levels of product differentiation tax rates are higher under no cooperation. Here, higher taxation results in higher (domestic) welfare, given the opportunity to shift emissions to country  $F$ .

In country  $F$ , taxation is lower for low levels of product differentiation than in country  $H$  and higher for higher levels. This is a response to the decreasing tax rate in  $H$  that shifts quantities (and emissions) to  $F$ . Tax rates in  $F$  decrease in the degree of product differentiation (but at a smaller rate than in  $H$ ) due to the quantity effect of weakened competition. If product differentiation is sufficiently large for the tax rate in  $H$  to be zero, the optimal tax rate in  $F$  increases in the degree of product differentiation. Tax rates in  $F$  are higher under no cooperation than under cooperation. This mirrors the tax rates in both cases in  $H$ . If  $H$  taxes emissions less under no cooperation,  $F$  has to set higher taxes to deter the export of emissions. If  $H$  sets higher tax rates under cooperation,  $F$  responds with lower tax rates.

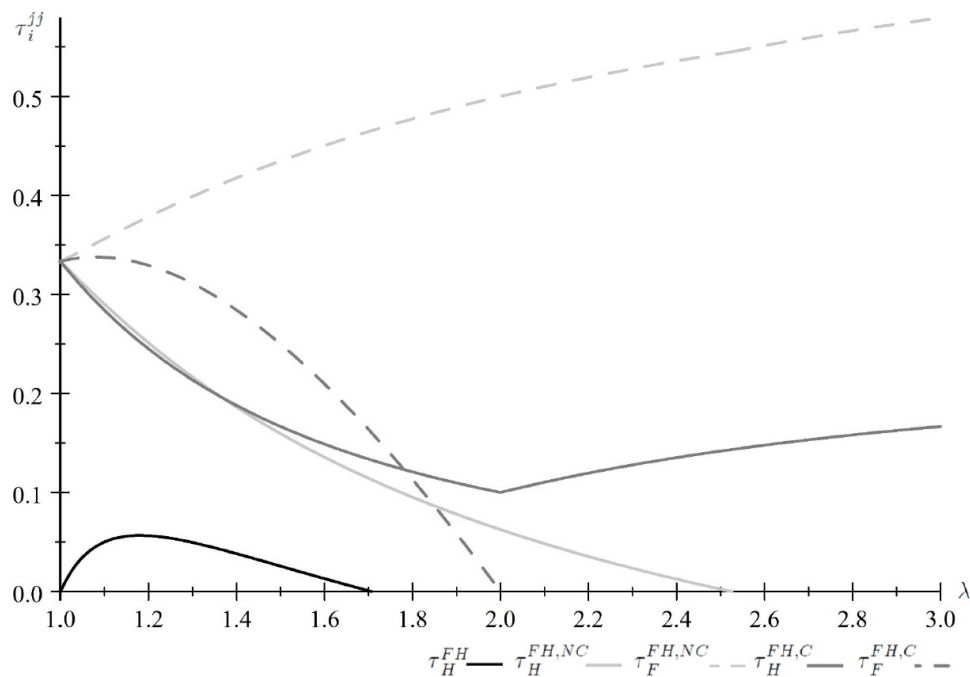


Figure 7:  $\tau_i^{jj}$  for unilateral, non-cooperative bilateral and coordinated bilateral taxation for  $FH$ .

In the location equilibrium  $FH$ , the optimal tax rate in  $H$  is hump-shaped in the case

of unilateral taxation. If both governments tax emissions non-cooperatively, the optimal tax rate in  $F$  increases in the degree of quality differentiation. The optimal tax rate in  $H$  decreases in quality differentiation because of the decreasing quantity. If the degree of quality differentiation is sufficiently large and the quantity in  $H$  sufficiently low, the optimal tax rate in  $H$  is zero. If product differentiation is small, tax rates in both countries are identical under cooperative and non-cooperative taxation. Under cooperation, tax rates in  $F$  decrease in the degree of product differentiation if the degree of product differentiation is sufficiently high. Tax rates in  $H$  also decrease the degree of product differentiation, but more slowly than in  $F$ . If the degree of product differentiation is sufficiently large so that the optimal tax rate in  $F$  is zero, the optimal tax rate increases in  $H$ .

### 5.2.3 Location Decision

In the first stage, both firms decide whether or not to relocate. First stage equilibrium profits and cut-off values for  $\phi$  can be found in Appendix A.5.

Figure 8 illustrates the resulting location Nash equilibria depending on the quality difference  $\lambda$  and the cost of relocation  $\phi$ .

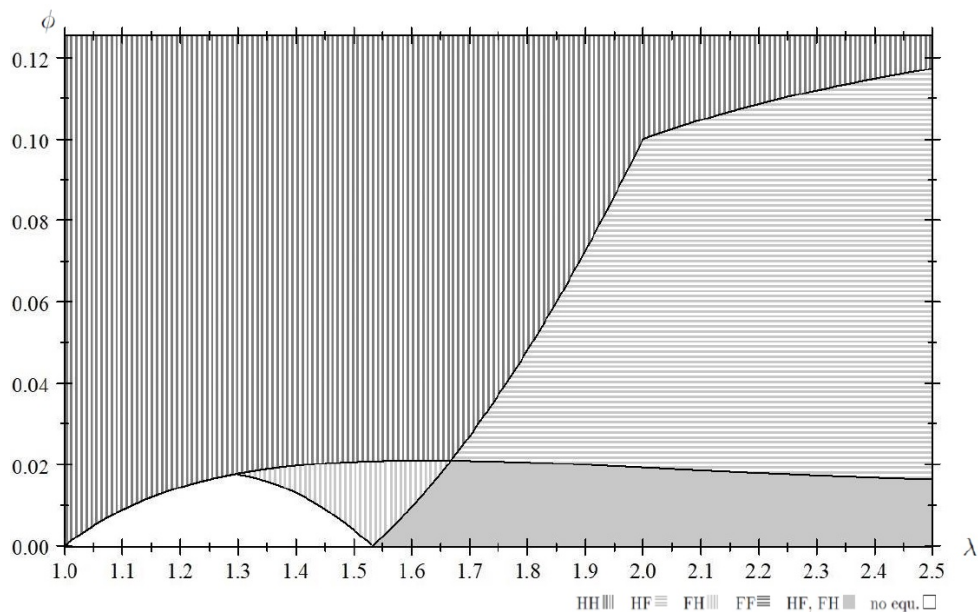


Figure 8: Location equilibria, bilateral, coordinated taxation.

If both governments apply an environmental tax in a coordinated manner to maximize joint welfare, we identify several combinations of  $\lambda$  and  $\phi$  with unique Nash equilib-

ria  $HH$  (vertical dark gray stripes),  $FH$  (vertical light gray stripes),  $HF$  (horizontal light gray stripes), an area characterized by multiple equilibria (solid light gray) and a region with no Nash equilibrium in pure strategies (white area). There is no  $FF$ -equilibrium.

Compared to non-cooperative taxation (please note the different scaling of the axes), the area of  $HH$ -equilibria has increased, and there is a large area in which the low-quality firm relocates to  $F$  (which is never the case under non-cooperative taxation). The low-quality firm relocates for relatively high levels of quality differentiation and intermediate levels of relocation cost. Compared to no taxation in  $F$ , the low-quality firm relocates only at higher quality differences.

Note that governments do not tax profits and that consumer surplus only results in  $H$ . Therefore for the quality difference being sufficiently large (and the relocation cost being sufficiently low), the high-quality firm may relocate to  $F$ .

To sum up, optimal environmental taxation under endogenous location decisions depends on quality differences as well as on the environmental taxation of the foreign country. Although environmental taxation might induce relocation of at least one firm, the quality difference is crucial for the location equilibrium and optimal tax rates.

## 6 Committed Policy

In this section, we consider an alternative timing of the game. We consider a case where the government commits to an environmental tax rate in the first stage of the game. Firms decide whether or not to relocate in the second stage and compete in prices in the last stage of the game. This is the timing analyzed by Ikefuji et al. (2016). In the following subsections, we present the backward induction solution of the three stages.

### 6.1 Price Competition

The last stage of the game, where firms set prices, is identical to the game described in section 3.

### 6.2 Location Decision

In the second stage, firms decide whether or not to relocate to  $F$  based on expected profits, given the government commitment and the decision of the other firm. Cut-off values for  $\phi$  can be found in Appendix A.6.

Both firms remain in  $H$  if  $\Pi_1^{HH} > \Pi_1^{FH}$  and  $\Pi_2^{HH} > \Pi_2^{HF}$ , i.e.  $\phi > \phi^{HH}$ . The high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ )

if  $\Pi_1^{FH} > \Pi_1^{HH}$  and  $\Pi_2^{FH} > \Pi_2^{FF}$ , i.e.  $\underline{\phi}^{FH} < \phi < \bar{\phi}^{FH}$ . Both firms relocate to  $F$  if  $\Pi_1^{FF} > \Pi_1^{HF}$  and  $\Pi_2^{FF} > \Pi_2^{FH}$ , i.e.  $\phi < \phi = \phi^{FF}$ . There is no equilibrium in which the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$ . For very high relocation cost, neither firm relocates. For intermediate relocation cost, it is always the high-quality firm that relocates. Both firms face a trade-off between paying the tax (higher variable cost) or relocating (higher fixed cost). Because of the higher quantity of the high-quality firm, the critical tax rate that makes relocation for a given relocation cost more favorable is lower than the critical tax rate for the low-quality firm. Therefore, if only one firm relocates, it is always the high-quality firm, but not the low-quality firm. So the government cannot commit to a tax rate that results in the high-quality firm staying in  $H$  and the low-quality firm relocating to  $F$ . This is similar to the case of non-cooperative bilateral taxation discussed in section 5. The reason is that commitment, as well as taxation decisions of the other country, make the government in  $H$  less flexible in choosing optimal tax rates.

### 6.3 Environmental Policy

Assume that in the first stage, the government in country  $H$  commits to a tax rate  $\tau_H$  to maximize social welfare, anticipating the relocation decisions in the second stage and price competition in the last stage. Equilibrium tax rates can be found in Appendix A.6.

If both firms remain in  $H$  (equilibrium  $HH$ ), social welfare is

$$W_H^{HH} = CS_H^{HH} + \Pi_1^{HH} + \Pi_2^{HH} + \tau_H (q_1^{HH} + q_2^{HH}) - \frac{1}{2} (q_1^{HH} + q_2^{HH})^2. \quad (38)$$

The welfare-maximizing tax rate  $\tau_H^{HH}$  is

$$\tau_H^{HH} = \frac{(2\lambda + 7)\lambda}{(\lambda + 1)(8\lambda + 1)}.$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), social welfare is

$$W_H^{FH} = CS_H^{FH} + \Pi_2^{FH} + \tau_H (q_2^{FH}) - \frac{1}{2} (q_2^{FH})^2. \quad (39)$$

The welfare-maximizing tax rate  $\tau_H^{FH}$  is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda-1)(4\lambda-2\lambda^2-1)}{\lambda(-9\lambda+8\lambda^2+2)} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}.$$

The difference to the scenario presented in section 3 stems from the fact that in the scenario discussed in section 3, there may be a welfare-maximizing tax rate for the case that the high-quality firm has already decided to relocate and the low-quality firm has decided to stay. But after the government has decided on a tax rate, this combination of firms' decisions cannot be an equilibrium. Our results presented in this section differ from the results of Ikefuji et al. (2016) because they consider duopolistic competition between firms offering a homogeneous good ( $\lambda = 1$ ).

## 7 Conclusion

This paper has analyzed the effect of an emission tax on the relocation decisions of firms when a duopolistic market is characterized by vertical quality differentiation. Especially, we have focused on the relationship between quality difference, relocation cost and optimal emission taxes in a two-country-setting for three cases: An environmental tax applied only by one country, non-cooperative environmental taxation in two countries, and coordinated environmental taxation.

If it is just the home country applying an environmental tax in a time-consistent manner, various Nash-equilibria of location decisions exist depending on the quality difference and relocation cost. The Nash-equilibria depend discontinuously on the cost of relocation  $\phi$  and the quality difference  $\lambda$ . The higher the quality difference, the higher is the probability of at least one firm relocating to  $F$ . A Nash-equilibrium where both firms relocate to  $F$  only exists for a limited range of relocation cost and quality difference. A lower marginal damage increases the area of  $\lambda$  and  $\phi$  where both firms remain in  $H$ . A higher marginal damage decreases the area of  $\lambda$  and  $\phi$  where both firms remain in  $H$ . If only the home country applies an environmental tax and commits to the tax rate before firms decide on relocation, the case where the high-quality firm remains in the home country and the low-quality firm relocates is not an equilibrium outcome of the game. If the environmental tax results in a relocation decision of only one firm, it is always the high-quality firm that relocates. So under commitment, the government in  $H$  cannot commit to a tax rate that motivates the low-quality firm to leave and the high-quality firm to stay.

If also the foreign country  $F$  applies an emission tax and both governments set taxes non-cooperatively, the high-quality firm never relocates to  $F$  in equilibrium. Similar to the case of commitment, the government in  $H$  cannot set a tax so that the high-quality

firm stays in  $H$  and the low-quality firm relocates to  $F$ . But if both countries cooperate, the high-quality firm is likely to relocate to the country where no output market exists. This result depends on the assumption that governments are not able to tax profits or consumer surplus and thus are restricted in using side-payments.

Our analysis shows the importance of the consideration of quality differences and taxing decisions in foreign countries. With respect to the pollution haven hypothesis, our analysis shows that in the unilateral case only a limited range of parameters exists where both firms relocate to country  $F$ . In addition, quality differences are crucial for relocation decisions of firms and therefore also for optimal environmental tax rates. If also the foreign country applies an environmental tax no such equilibrium exists for uncooperative taxation. This finding implies that emission taxation of competing governments does not result in a race to the bottom. Taxes are higher under non-cooperative tax setting when compared to only one country taxing emissions.

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## Appendix

### A.1 Time Consistent Policy

#### Price Competition

If both firms stay in the home country (equilibrium  $HH$ ), equilibrium prices and quantities are

$$\begin{aligned} p_1^{HH} &= \frac{2\lambda(\lambda-1) + 3\lambda\tau_H}{4\lambda-1}, p_2^{HH} = \frac{\lambda-1 + \tau_H(1+2\lambda)}{4\lambda-1} \\ q_1^{HH} &= \frac{2\lambda - \tau_H}{4\lambda-1}, q_2^{HH} = \frac{(1-2\tau_H)\lambda}{4\lambda-1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{HH} = \frac{(\lambda-1)(\tau_H-2\lambda)^2}{(4\lambda-1)^2}, \Pi_2^{HH} = \frac{\lambda(\lambda-1)(2\tau_H-1)^2}{(4\lambda-1)^2}.$$

If the high-quality firm remains in  $H$ , the low-quality firm relocates (equilibrium  $HF$ ), equilibrium prices and quantities are

$$\begin{aligned} p_1^{HF} &= \frac{2\lambda(\lambda-1) + 2\lambda\tau_H}{4\lambda-1}, p_2^{HF} = \frac{(\lambda + \tau_H - 1)}{4\lambda-1}, \\ q_1^{HF} &= \frac{2\lambda(\lambda-1) - \tau_H(2\lambda-1)}{4\lambda^2 - 5\lambda + 1}, q_2^{HF} = \lambda \frac{\lambda + \tau_H - 1}{4\lambda^2 - 5\lambda + 1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{HF} = \frac{(2\lambda(\lambda-1) - (2\lambda-1)\tau_H)^2}{(\lambda-1)(4\lambda-1)^2}, \Pi_2^{HF} = \frac{\lambda(\lambda + \tau_H - 1)^2}{(\lambda-1)(4\lambda-1)^2} - \phi.$$

If the high-quality firm relocates, the low-quality firm stays in  $H$  (equilibrium  $FH$ ), equilibrium prices and quantities are

$$\begin{aligned} p_1^{FH} &= \frac{2\lambda(\lambda-1) + \lambda\tau_H}{4\lambda-1}, p_2^{FH} = \frac{\lambda + 2\lambda\tau_H - 1}{4\lambda-1}, \\ q_1^{FH} &= \frac{\lambda(2(\lambda-1) + \tau_H)}{4\lambda^2 - 5\lambda + 1}, q_2^{FH} = \frac{\lambda(\lambda-1 - \tau_H(2\lambda-1))}{4\lambda^2 - 5\lambda + 1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{FH} = \frac{\lambda^2(2(\lambda-1) + \tau_H)^2}{(\lambda-1)(4\lambda-1)^2} - \phi, \Pi_2^{FH} = \frac{\lambda(\lambda-1 - \tau_H(2\lambda-1))^2}{(\lambda-1)(4\lambda-1)^2}.$$

If both firms relocate (equilibrium  $FF$ ), equilibrium prices and quantities are

$$\begin{aligned} p_1^{FF} &= \frac{2\lambda(\lambda-1)}{4\lambda-1}, p_2^{FF} = \frac{\lambda-1}{4\lambda-1}, \\ q_1^{FF} &= \frac{2\lambda}{4\lambda-1}, q_2^{FF} = \frac{\lambda}{4\lambda-1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{FF} = \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \phi, \Pi_2^{FF} = \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \phi.$$

### Environmental Policy

If both firms remain in country  $H$  (equilibrium  $HH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HH} = \frac{(2\lambda+7)\lambda}{(\lambda+1)(8\lambda+1)}.$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HF} = \begin{cases} \frac{\lambda(\lambda-1)(9\lambda-4\lambda^2-3)}{-3\lambda-\lambda^2+4\lambda^3+1} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8} \end{cases}.$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda-1)(4\lambda-2\lambda^2-1)}{\lambda(-9\lambda+8\lambda^2+2)} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}.$$

### Location Decision

If both firms stay in country  $H$  (equilibrium  $HH$ ), equilibrium profits are

$$\pi_1^{HH} = \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2}, \pi_2^{HH} = \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2}.$$

If the high-quality firm stays in  $H$  and the low-quality firm relocates to  $F$  (equilibrium

$HF$ ), equilibrium profits are given as

$$\begin{aligned}\pi_1^{HF} &= \begin{cases} \frac{\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8} \end{cases} \\ \pi_2^{HF} &= \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8}. \end{cases}\end{aligned}$$

If the high-quality firm relocates to  $F$  and the low-quality firm stays in  $H$  (equilibrium  $FH$ ), equilibrium profits are

$$\begin{aligned}\pi_1^{FH} &= \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-9\lambda+2)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases} \\ \pi_2^{FH} &= \begin{cases} \frac{(\lambda-1)^3(3\lambda-1)^2}{\lambda(8\lambda^2-9\lambda+2)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1. \end{cases}\end{aligned}$$

If both firms relocate to  $F$  (equilibrium  $FF$ ), equilibrium profits are

$$\begin{aligned}\pi_1^{FF} &= \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} \\ \pi_2^{FF} &= \frac{\lambda(\lambda-1)}{(4\lambda-1)^2}.\end{aligned}$$

Both firms stay in country  $H$  (equilibrium  $HH$ ) if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 1.2740 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-9\lambda+2)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } 1.2740 \leq \lambda < \frac{1}{2}\sqrt{2} + 1 \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1, \end{cases}$$

where  $\phi^{HH} = \max\{\phi_1^{HH}, \phi_2^{HH}\}$ , with

$$\phi_1^{HH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-9\lambda+2)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}$$

$$\phi_2^{HH} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8}. \end{cases}$$

Firm 1 remains in  $H$ , but firm 2 relocates to  $F$  (equilibrium  $HF$ ) if  $\underline{\phi}^{HF} < \phi < \overline{\phi}^{HF}$ , with

$$\underline{\phi}^{HF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8} \end{cases}$$

$$\overline{\phi}^{HF} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8}. \end{cases}$$

Firm 1 relocates to  $F$  and firm 2 remains in  $H$  if  $\underline{\phi}^{FH} < \phi < \overline{\phi}^{FH}$ , with

$$\underline{\phi}^{FH} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)^3(3\lambda-1)^2}{\lambda(8\lambda^2-9\lambda+2)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}$$

$$\overline{\phi}^{FH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-9\lambda+2)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(\lambda+1)^2(8\lambda+1)^2} & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1. \end{cases}$$

Both firms relocate to  $F$  (equilibrium  $FF$ ) if  $\phi < \phi^{FF}$ , with

$$\phi^{FF} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)^3(3\lambda-1)^2}{\lambda(8\lambda^2-9\lambda+2)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}$$

where  $\phi^{FF} = \min\{\phi_1^{FF}, \phi_2^{FF}\}$ , with

$$\begin{aligned}\phi_1^{FF} &= \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-4\lambda^3+\lambda^2+3\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{33} + \frac{9}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{33} + \frac{9}{8} \end{cases} \\ \phi_2^{FF} &= \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)^3(3\lambda-1)^2}{\lambda(8\lambda^2-9\lambda+2)^2} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1. \end{cases}\end{aligned}$$

## A.2 Damage Function $D = \frac{1}{4}q^2$

### Environmental Policy

If both firms remain in country  $H$  (equilibrium  $HH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HH} = \begin{cases} \frac{\lambda(11-2\lambda)}{12\lambda^2+14\lambda+1} & \text{if } \lambda < \frac{11}{2} \\ 0 & \text{if } \lambda \geq \frac{11}{2}. \end{cases}$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HF} = \begin{cases} \frac{2\lambda(1-\lambda)(4\lambda^2-7\lambda+2)}{8\lambda^3-6\lambda^2-2\lambda+1} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8}. \end{cases}$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{FH} = \begin{cases} \frac{(1-\lambda)(6\lambda^2-9\lambda+2)}{\lambda(12\lambda^2-14\lambda+3)} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4}. \end{cases}$$

### Location Decision

If both firms remain in  $H$  (equilibrium  $HH$ ), equilibrium profits are

$$\begin{aligned}\pi_1^{HH} &= \begin{cases} \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{11}{2} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{11}{2} \end{cases} \\ \pi_2^{HH} &= \begin{cases} \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{11}{2} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{11}{2}. \end{cases}\end{aligned}$$

If the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  (equilibrium  $HF$ ), profits are

$$\begin{aligned}\pi_1^{HF} &= \begin{cases} \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8} \end{cases} \\ \pi_2^{HF} &= \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8}. \end{cases}\end{aligned}$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), equilibrium profits are

$$\begin{aligned}\pi_1^{FH} &= \begin{cases} \frac{(\lambda-1)(6\lambda^2-7\lambda+2)^2}{(12\lambda^2-14\lambda+3)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \end{cases} \\ \pi_2^{FH} &= \begin{cases} \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(12\lambda^2-14\lambda+3)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4}. \end{cases}\end{aligned}$$

If both firms relocate to  $F$  (equilibrium  $FF$ ), profits are

$$\begin{aligned}\pi_1^{FF} &= \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} \\ \pi_2^{FF} &= \frac{\lambda(\lambda-1)}{(4\lambda-1)^2}.\end{aligned}$$

Both firms remain in  $H$  if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} - \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < 1.319 \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } 1.319 \leq \lambda < \frac{11}{2} \\ 0 & \text{if } \lambda \geq \frac{11}{2}, \end{cases}$$

with  $\phi^{HH} = \max\{\phi_1^{HH}, \phi_2^{HH}\}$ , with

$$\phi_1^{HH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(6\lambda^2-7\lambda+2)^2}{(12\lambda^2-14\lambda+3)^2} - \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \leq \lambda < \frac{11}{2} \\ 0 & \text{if } \lambda \geq \frac{11}{2} \end{cases}$$

$$\phi_2^{HH} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} - \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \frac{1}{8}\sqrt{17} + \frac{7}{8} \leq \lambda < \frac{11}{2} \\ 0 & \text{if } \frac{11}{2} \geq \lambda. \end{cases}$$

The high-quality firm remains in  $H$  and the low-quality firm relocates (equilibrium  $HF$ ) if  $\underline{\phi}^{HF} < \phi < \bar{\phi}^{HF}$ , with

$$\underline{\phi}^{HF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8} \end{cases}$$

$$\bar{\phi}^{HF} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{\lambda(\lambda-1)(2\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} - \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{\lambda(\lambda-1)(4\lambda-1)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \frac{1}{8}\sqrt{17} + \frac{7}{8} \leq \lambda < \frac{11}{2} \\ 0 & \text{if } \lambda \geq \frac{11}{2}. \end{cases}$$

The high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ) if  $\underline{\phi}^{FH} < \phi < \bar{\phi}^{FH}$ , with

$$\underline{\phi}^{FH} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(12\lambda^2-14\lambda+3)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \end{cases}$$

$$\bar{\phi}^{FH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(6\lambda^2-7\lambda+2)^2}{(12\lambda^2-14\lambda+3)^2} - \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{9\lambda^2(\lambda-1)(2\lambda+3)^2}{(12\lambda^2+14\lambda+1)^2} & \text{if } \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \leq \lambda < \frac{11}{2} \\ 0 & \text{if } \frac{11}{2} \geq \lambda. \end{cases}$$

Both firms relocate to  $F$  (equilibrium  $FF$ ) if  $\phi < \phi^{FF}$ , with

$$\phi^{FF} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(12\lambda^2-14\lambda+3)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4}, \end{cases}$$



where  $\phi^{FF} = \min\{\phi_1^{FF}, \phi_2^{FF}\}$ , with

$$\begin{aligned}\phi_1^{FF} &= \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(-8\lambda^3+6\lambda^2+2\lambda-1)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{17} + \frac{7}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{17} + \frac{7}{8} \end{cases} \\ \phi_2^{FF} &= \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(12\lambda^2-14\lambda+3)^2} & \text{if } \lambda < \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{12}\sqrt{3}\sqrt{11} + \frac{3}{4}. \end{cases}\end{aligned}$$

### A.3 Damage Function $D = \frac{3}{4}q^2$

#### 7.0.1 Environmental Policy

If both firms remain in  $H$  (equilibrium  $HH$ ), the welfare-maximizing tax rate is

$$\tau_H^{HH} = \frac{1}{2}.$$

If the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  (equilibrium  $HF$ ), the welfare-maximizing tax rate is

$$\tau_H^{HF} = \begin{cases} \frac{2\lambda(\lambda-1)(-4\lambda^2+11\lambda-4)}{(4\lambda-3)(2\lambda^2+2\lambda-1)} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8}. \end{cases}$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), the welfare-maximizing tax rate is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda-1)(-2\lambda^2+7\lambda-2)}{\lambda(-22\lambda+20\lambda^2+5)} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}. \end{cases}$$

#### Location Decision

If both firms remain in  $H$  (equilibrium  $HH$ ), profits are

$$\begin{aligned}\pi_1^{HH} &= \frac{(\lambda-1)}{4} \\ \pi_2^{HH} &= 0.\end{aligned}$$

If the high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  (equi-

librium  $HF$ ), profits are

$$\begin{aligned}\pi_1^{HF} &= \begin{cases} \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8} \end{cases} \\ \pi_2^{HF} &= \begin{cases} \frac{9\lambda(\lambda-1)(2\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8}. \end{cases}\end{aligned}$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$  (equilibrium  $FH$ ), profits are

$$\begin{aligned}\pi_1^{FH} &= \begin{cases} \frac{(\lambda-1)(10\lambda^2-9\lambda+2)^2}{(20\lambda^2-22\lambda+5)^2} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4} \end{cases} \\ \pi_2^{FH} &= \begin{cases} \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(20\lambda^2-22\lambda+5)^2} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}. \end{cases}\end{aligned}$$

If both firms relocate to  $F$  (equilibrium  $FF$ ), profits are

$$\begin{aligned}\pi_1^{FF} &= \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} \\ \pi_2^{FF} &= \frac{\lambda(\lambda-1)}{(4\lambda-1)^2}.\end{aligned}$$

Both firms remain in  $H$  (equilibrium  $HH$ ) if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \begin{cases} \frac{9\lambda(\lambda-1)(2\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < 1.3105 \\ \frac{(\lambda-1)(10\lambda^2-9\lambda+2)^2}{(20\lambda^2-22\lambda+5)^2} - \frac{(\lambda-1)}{4} & \text{if } 1.3105 \leq \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)}{4} & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}, \end{cases}$$

with  $\phi^{HH} = \max\{\phi_1^{HH}, \phi_2^{HH}\}$  where

$$\phi_1^{HH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(10\lambda^2-9\lambda+2)^2}{(20\lambda^2-22\lambda+5)^2} - \frac{(\lambda-1)}{4} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)}{4} & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4} \end{cases}$$

$$\phi_2^{HH} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{9\lambda(\lambda-1)(2\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8}. \end{cases}$$

The high-quality firm remains in  $H$  and the low-quality firm relocates to  $F$  ( $HF$ ) if  $\underline{\phi}^{HF} < \phi < \overline{\phi}^{HF}$ , with

$$\underline{\phi}^{HF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8} \end{cases}$$

$$\overline{\phi}^{HF} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{9\lambda(\lambda-1)(2\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8}. \end{cases}$$

The high-quality firm relocates and the low-quality firm remains in  $H$  if  $\underline{\phi}^{FH} < \phi < \overline{\phi}^{FH}$ , with

$$\underline{\phi}^{FH} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(20\lambda^2-22\lambda+5)^2} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4} \end{cases}$$

$$\overline{\phi}^{FH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(10\lambda^2-9\lambda+2)^2}{(20\lambda^2-22\lambda+5)^2} - \frac{(\lambda-1)}{4} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{(\lambda-1)}{4} & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}. \end{cases}$$

Both firms relocate to  $F$  if  $\phi < \phi^{FF}$ , with

$$\phi^{FF} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(20\lambda^2-22\lambda+5)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8} \end{cases}$$

and  $\phi^{FF} = \min\{\phi_1^{FF}, \phi_2^{FF}\}$ , with

$$\phi_1^{FF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{4\lambda^2(\lambda-1)}{(4\lambda-1)^2} - \frac{4\lambda^2(\lambda-1)^3(4\lambda-1)^2}{(8\lambda^3+2\lambda^2-10\lambda+3)^2} & \text{if } \lambda < \frac{1}{8}\sqrt{57} + \frac{11}{8} \\ 0 & \text{if } \lambda \geq \frac{1}{8}\sqrt{57} + \frac{11}{8} \end{cases}$$

$$\phi_2^{FF} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)}{(4\lambda-1)^2} - \frac{4(\lambda-1)^3(3\lambda-1)^2}{\lambda(20\lambda^2-22\lambda+5)^2} & \text{if } \lambda < \frac{1}{4}\sqrt{33} + \frac{7}{4} \\ 0 & \text{if } \lambda \geq \frac{1}{4}\sqrt{33} + \frac{7}{4}. \end{cases}$$

#### A.4. Environmental Taxes in Both Countries - Non-cooperative Taxation

##### Price Competition

If both firms stay in the home country (equilibrium  $HH$ ), equilibrium prices and quantities are

$$p_1^{HH} = \frac{2\lambda(\lambda-1) + 3\lambda\tau_H}{4\lambda-1}, p_2^{HH} = \frac{\lambda-1 + \tau_H(1+2\lambda)}{4\lambda-1},$$

$$q_1^{HH} = \frac{2\lambda - \tau_H}{4\lambda-1}, q_2^{HH} = \frac{(1-2\tau_H)\lambda}{4\lambda-1}.$$

Equilibrium profits are

$$\Pi_1^{HH} = \frac{(\lambda-1)(\tau_H-2\lambda)^2}{(4\lambda-1)^2}, \Pi_2^{HH} = \frac{\lambda(\lambda-1)(2\tau_H-1)^2}{(4\lambda-1)^2}.$$

If the high-quality firm remains in  $H$ , the low-quality firm relocates (equilibrium  $HF$ ), equilibrium prices and quantities are

$$p_1^{HF} = \lambda \frac{2(\lambda-1) + \tau_F + 2\tau_H}{4\lambda-1}, p_2^{HF} = \frac{\lambda + \tau_H + 2\lambda\tau_F - 1}{4\lambda-1},$$

$$q_1^{HF} = \frac{2\lambda(\lambda-1) - (2\lambda-1)\tau_H + \lambda\tau_F}{4\lambda^2 - 5\lambda + 1}, q_2^{HF} = \frac{\lambda(\lambda-1) + \lambda\tau_H - \lambda\tau_F(2\lambda-1)}{4\lambda^2 - 5\lambda + 1}.$$

Equilibrium profits are

$$\Pi_1^{HF} = \frac{(2\lambda(\lambda-1) - (2\lambda-1)\tau_H + \lambda\tau_F)^2}{(4\lambda-1)(4\lambda^2 - 5\lambda + 1)}, \Pi_2^{HF} = \frac{\lambda(\lambda-1 + \tau_H - (2\lambda-1)\tau_F)^2}{(\lambda-1)(4\lambda-1)^2} - \phi.$$

If the high-quality firm relocates, the low-quality firm stays in  $H$  (equilibrium  $FH$ ),

equilibrium prices and quantities are

$$\begin{aligned} p_1^{FH} &= \frac{(2\lambda(\lambda-1) + 2\lambda\tau_F + \lambda\tau_H)}{4\lambda-1}, p_2^{FH} = \frac{(\lambda-1 + \tau_F + 2\lambda\tau_H)}{4\lambda-1} \\ q_1^{FH} &= \frac{(2\lambda(\lambda-1) - \tau_F(2\lambda-1) + \lambda\tau_H)}{4\lambda^2 - 5\lambda + 1}, q_2^{FH} = \frac{\lambda(\lambda-1 + \tau_F - (2\lambda-1)\tau_H)}{4\lambda^2 - 5\lambda + 1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{FH} = \frac{(2\lambda(\lambda-1) - \tau_F(2\lambda-1) + \lambda\tau_H)^2}{(\lambda-1)(4\lambda-1)^2} - \phi, \Pi_2^{FH} = \frac{\lambda(\lambda-1 + \tau_F - (2\lambda-1)\tau_H)^2}{(\lambda-1)(4\lambda-1)^2}.$$

If both firms relocate (equilibrium  $FF$ ), equilibrium prices and quantities are

$$\begin{aligned} p_1^{FF} &= \frac{2\lambda(\lambda-1) + 3\lambda\tau_F}{4\lambda-1}, p_2^{FF} = \frac{\lambda-1 + \tau_F(2\lambda+1)}{4\lambda-1}, \\ q_1^{FF} &= \frac{2\lambda - \tau_F}{4\lambda-1}, q_2^{FF} = \frac{\lambda(1-2\tau_F)}{4\lambda-1}. \end{aligned}$$

Equilibrium profits are

$$\Pi_1^{FF} = \frac{(\lambda-1)(2\lambda - \tau_F)^2}{(4\lambda-1)^2} - \phi, \Pi_2^{FF} = \frac{\lambda(\lambda-1)(1-2\tau_F)^2}{(4\lambda-1)^2} - \phi.$$

## Environmental Policy

If both firms remain in country  $H$  (equilibrium  $HH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HH,NC} = \frac{(2\lambda+7)\lambda}{(\lambda+1)(8\lambda+1)}.$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ), the resulting welfare maximizing tax rates are

$$\begin{aligned} \tau_H^{HF,NC} &= \begin{cases} \frac{-6\lambda^3+17\lambda^2-11\lambda+1}{\lambda+6\lambda^2-4} & \text{if } \lambda < 1.9267 \\ 0 & \text{if } \lambda \geq 1.9267 \end{cases} \\ \tau_F^{HF,NC} &= \begin{cases} \frac{2\lambda^2-1}{6\lambda^3+\lambda^2-4\lambda} & \text{if } \lambda < 1.9267 \\ \frac{(2\lambda^2-1)(\lambda-1)}{\lambda(2\lambda-1)(6\lambda-5)} & \text{if } \lambda \geq 1.9267 \end{cases}. \end{aligned}$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ),

the resulting welfare maximizing tax rate are

$$\tau_H^{FH,NC} = \begin{cases} \frac{(2\lambda^3 - 6\lambda^2 + 2\lambda + 1)}{-8\lambda^3 + 3\lambda^2 + 2\lambda} & \text{if } \lambda < 2.5257 \\ 0 & \text{if } \lambda \geq 2.5257 \end{cases}$$

$$\tau_F^{FH,NC} = \begin{cases} \frac{(6\lambda^2 - 7\lambda + 2)}{8\lambda^2 - 3\lambda - 2} & \text{if } \lambda < 2.5257 \\ \frac{(6\lambda^3 - 10\lambda^2 + 4\lambda)}{8\lambda^3 - 8\lambda^2 + 1} & \text{if } \lambda \geq 2.5257 \end{cases}.$$

If both firms relocate (equilibrium  $FF$ ), the resulting welfare maximizing tax rate is

$$\tau_F^{FF} = \frac{2\lambda(5\lambda + 4)}{12\lambda^2 + 14\lambda + 1}.$$

### Location Decision

If both firms remain in  $H$  (equilibrium  $HH$ ), profits are

$$\pi_1^{HH} = \frac{\lambda^2(\lambda - 1)(4\lambda + 5)^2}{(8\lambda^2 + 9\lambda + 1)^2}$$

$$\pi_2^{HH} = \frac{\lambda(\lambda - 1)^3}{(8\lambda^2 + 9\lambda + 1)^2}$$

If firm 1 remains in  $H$  and firm 2 relocates to  $F$  (equilibrium  $HF$ ), profits are

$$\pi_1^{HF} = \begin{cases} \frac{\lambda^2(\lambda - 1)(6\lambda - 5)^2}{(6\lambda^2 + \lambda - 4)^2} & \text{if } \lambda < 1.9267 \\ \frac{(\lambda - 1)(6\lambda^2 - 6\lambda + 1)^2}{(12\lambda^2 - 16\lambda + 5)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

$$\pi_2^{HF} = \begin{cases} \frac{(\lambda - 1)(2\lambda - 1)^2}{\lambda(6\lambda^2 + \lambda - 4)^2} & \text{if } \lambda < 1.9267 \\ \frac{(\lambda - 1)^3}{\lambda(6\lambda - 5)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

If firm 1 relocates to  $F$  and firm 2 remains in  $H$  (equilibrium  $FH$ ), profits are

$$\pi_1^{FH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(-8\lambda^2+3\lambda+2)^2} & \text{if } \lambda < 2.5257 \\ \frac{4\lambda^2(\lambda-1)^3}{(-4\lambda^2+2\lambda+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

$$\pi_2^{FH} = \begin{cases} \frac{(\lambda-1)(-3\lambda^2+\lambda+1)^2}{\lambda(-8\lambda^2+3\lambda+2)^2} & \text{if } \lambda < 2.5257 \\ \frac{\lambda(2\lambda^2-1)^2(\lambda-1)}{(8\lambda^3-8\lambda^2+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

If both firms relocate to  $F$  (equilibrium  $FF$ ), profits are

$$\pi_1^{FF} = \frac{36\lambda^2(\lambda-1)(\lambda+1)^2}{(12\lambda^2+14\lambda+1)^2}$$

$$\pi_2^{FF} = \frac{4\lambda^4-3\lambda^2-\lambda}{(12\lambda^2+14\lambda+1)^2}$$

Both firms remain in  $H$  if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{\lambda(6\lambda^2+\lambda-4)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 1.9267 \\ \frac{(\lambda-1)^3}{\lambda(6\lambda-5)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

with  $\phi^{HH} = \max\{\phi_1^{HH}, \phi_2^{HH}\}$ , where

$$\phi_1^{HH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(-8\lambda^2+3\lambda+2)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2.5257 \\ \frac{4\lambda^2(\lambda-1)^3}{(-4\lambda^2+2\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

$$\phi_2^{HH} = \pi_2^{FH} - \pi_2^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{\lambda(6\lambda^2+\lambda-4)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 1.9267 \\ \frac{(\lambda-1)^3}{\lambda(6\lambda-5)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

Firm 1 remains in  $H$  and firm 2 relocates (equilibrium  $HF$ ) if  $\underline{\phi}^{HF} < \phi < \overline{\phi}^{HF}$ , with

$$\underline{\phi}^{HF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{36\lambda^2(\lambda-1)(\lambda+1)^2}{(12\lambda^2+14\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(6\lambda-5)^2}{(6\lambda^2+\lambda-4)^2} & \text{if } \lambda < 1.9267 \\ \frac{36\lambda^2(\lambda-1)(\lambda+1)^2}{(12\lambda^2+14\lambda+1)^2} - \frac{(\lambda-1)(6\lambda^2-6\lambda+1)^2}{(12\lambda^2-16\lambda+5)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

$$\overline{\phi}^{HF} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{\lambda(6\lambda^2+\lambda-4)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 1.9267 \\ \frac{(\lambda-1)^3}{\lambda(6\lambda-5)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

Firm 1 relocates to  $F$  and firm 2 remains in  $H$  (equilibrium  $FH$ ) if  $\underline{\phi}^{FH} < \phi < \overline{\phi}^{FH}$ , with

$$\underline{\phi}^{FH} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{4\lambda^4-3\lambda^2-\lambda}{(12\lambda^2+14\lambda+1)^2} - \frac{(\lambda-1)(-3\lambda^2+\lambda+1)^2}{\lambda(-8\lambda^2+3\lambda+2)^2} & \text{if } \lambda < 2.5257 \\ \frac{4\lambda^4-3\lambda^2-\lambda}{(12\lambda^2+14\lambda+1)^2} - \frac{\lambda(2\lambda^2-1)^2(\lambda-1)}{(8\lambda^3-8\lambda^2+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

$$\overline{\phi}^{FH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^4}{(-8\lambda^2+3\lambda+2)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2.5257 \\ \frac{4\lambda^2(\lambda-1)^3}{(-4\lambda^2+2\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

Both firms relocate if  $\phi < \phi^{FF} = 0$ , with  $\phi^{FF} = \min\{\phi_1^{FF}, \phi_2^{FF}\}$  where

$$\phi_1^{FF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{36\lambda^2(\lambda-1)(\lambda+1)^2}{(12\lambda^2+14\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(6\lambda-5)^2}{(6\lambda^2+\lambda-4)^2} & \text{if } \lambda < 1.9267 \\ \frac{36\lambda^2(\lambda-1)(\lambda+1)^2}{(12\lambda^2+14\lambda+1)^2} - \frac{(\lambda-1)(6\lambda^2-6\lambda+1)^2}{(12\lambda^2-16\lambda+5)^2} & \text{if } \lambda \geq 1.9267 \end{cases}$$

$$\phi_2^{FF} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{4\lambda^4-3\lambda^2-\lambda}{(12\lambda^2+14\lambda+1)^2} - \frac{(\lambda-1)(-3\lambda^2+\lambda+1)^2}{\lambda(-8\lambda^2+3\lambda+2)^2} & \text{if } \lambda < 2.5257 \\ \frac{4\lambda^4-3\lambda^2-\lambda}{(12\lambda^2+14\lambda+1)^2} - \frac{\lambda(2\lambda^2-1)^2(\lambda-1)}{(8\lambda^3-8\lambda^2+1)^2} & \text{if } \lambda \geq 2.5257 \end{cases}$$

## A.5 Environmental Taxes in Both Countries - Coordinated Taxation

### Environmental Policy

If both firms remain in country  $H$  (equilibrium  $HH$ ), the resulting welfare maximizing tax rate is

$$\tau_H^{HH,C} = \frac{(2\lambda + 7)\lambda}{(\lambda + 1)(8\lambda + 1)}.$$

If firm 1 remains in country  $H$ , but firm 2 relocates to country  $F$  (equilibrium  $HF$ ),



the resulting welfare maximizing tax rates are

$$\begin{aligned}\tau_H^{HF,C} &= \begin{cases} \frac{(\lambda-2)(1-2\lambda)}{2\lambda+1} & \text{if } \lambda < 2 \\ 0 & \text{if } \lambda \geq 2 \end{cases} \\ \tau_F^{HF,C} &= \begin{cases} \frac{1}{\lambda(2\lambda+1)} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(-2\lambda+2\lambda^2-1)}{\lambda(-11\lambda+8\lambda^2+5)} & \text{if } \lambda \geq 2 \end{cases} .\end{aligned}$$

If firm 1 relocates to country  $F$ , but firm 2 remains in country  $H$  (equilibrium  $FH$ ), the resulting welfare maximizing tax rates are

$$\begin{aligned}\tau_H^{FH,C} &= \begin{cases} \frac{1}{\lambda(2\lambda+1)} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(-2\lambda+2\lambda^2-1)}{\lambda(-11\lambda+8\lambda^2+5)} & \text{if } \lambda \geq 2 \end{cases} \\ \tau_F^{FH,C} &= \begin{cases} \frac{(2\lambda-1)(2-\lambda)}{2\lambda+1} & \text{if } \lambda < 2 \\ 0 & \text{if } \lambda \geq 2 \end{cases} .\end{aligned}$$

If both firms relocate (equilibrium  $FF$ ), the resulting welfare maximizing tax rate is

$$\tau_F^{FF,C} = \frac{2\lambda(5\lambda+4)}{12\lambda^2+14\lambda+1}.$$

## Location Decision

If both firms remain in  $H$  (equilibrium  $HH$ ), profits are

$$\begin{aligned}\pi_1^{HH} &= \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} \\ \pi_2^{HH} &= \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2}\end{aligned}$$

If firm 1 remains in  $H$  and firm 2 relocates to  $F$  (equilibrium  $HF$ ), profits are

$$\begin{aligned}\pi_1^{HF,C} &= \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases} \\ \pi_2^{HF,C} &= \begin{cases} \frac{(\lambda-1)}{\lambda(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}\end{aligned}$$

If firm 1 relocates to  $F$  and firm 2 remains in  $H$  (equilibrium  $FH$ ), profits are

$$\begin{aligned}\pi_1^{FH,C} &= \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases} \\ \pi_2^{FH,C} &= \begin{cases} \frac{\lambda-1}{\lambda(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}\end{aligned}$$

If both firms relocate to  $F$  (equilibrium  $FF$ ), profits are

$$\begin{aligned}\pi_1^{FF,C} &= \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} \\ \pi_2^{FF,C} &= \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2}\end{aligned}$$

Both firms remain in  $H$  if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \begin{cases} \frac{(\lambda-1)}{\lambda(2\lambda+1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 1.6678 \\ \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } 1.6678 \leq \lambda < 2 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2 \end{cases}$$

with  $\phi^{HH} = \max\{\phi_1^{HH}, \phi_2^{HH}\}$ , where

$$\phi_1^{HH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2 \end{cases}$$

$$\phi_2^{HH} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{(\lambda-1)}{\lambda(2\lambda+1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2 \end{cases}$$

Firm 1 remains in  $H$  and firm 2 relocates (equilibrium  $HF$ ) if  $\underline{\phi}^{HF} < \phi < \overline{\phi}^{HF}$ , with

$$\underline{\phi}^{HF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}$$

$$\overline{\phi}^{HF} = \pi_2^{HF} - \pi_2^{HH} = \begin{cases} \frac{(\lambda-1)}{\lambda(2\lambda+1)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} - \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2 \end{cases}$$

Firm 1 relocates to  $F$  and firm 2 remains in  $H$  (equilibrium  $FH$ ) if  $\underline{\phi}^{FH} < \phi < \overline{\phi}^{FH}$ , with

$$\underline{\phi}^{FH} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} - \frac{\lambda-1}{\lambda(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}$$

$$\overline{\phi}^{FH} = \pi_1^{FH} - \pi_1^{HH} = \begin{cases} \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} - \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} & \text{if } \lambda \geq 2 \end{cases}$$

Both firms relocate if  $\phi < \phi^{FF} = 0$ , with  $\phi^{FF} = \min\{\phi_1^{FF}, \phi_2^{FF}\}$  where

$$\phi_1^{FF} = \pi_1^{FF} - \pi_1^{HF} = \begin{cases} \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(2\lambda-1)^2}{(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{\lambda^2(\lambda-1)(4\lambda+5)^2}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(2\lambda-1)^4}{(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}$$

$$\phi_2^{FF} = \pi_2^{FF} - \pi_2^{FH} = \begin{cases} \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} - \frac{\lambda-1}{\lambda(2\lambda+1)^2} & \text{if } \lambda < 2 \\ \frac{\lambda(\lambda-1)^3}{(8\lambda^2+9\lambda+1)^2} - \frac{(\lambda-1)(\lambda^2-\lambda+1)^2}{\lambda(8\lambda^2-11\lambda+5)^2} & \text{if } \lambda \geq 2 \end{cases}$$

## A.6. Committed Policy

### Location Decision

Both firms remain in  $H$  if  $\phi > \phi^{HH}$ , with

$$\phi^{HH} = \frac{\tau_H (2\lambda - 1) (4\lambda (\lambda - 1) + \tau_H)}{(\lambda - 1) (4\lambda - 1)^2}$$

Firm 1 relocates to  $F$  and firm 2 remains in  $H$  (equilibrium  $FH$ ) if  $\underline{\phi}^{FH} < \phi < \bar{\phi}^{FH}$ , with

$$\begin{aligned} \underline{\phi}^{FH} &= \pi_2^{FF} - \pi_2^{FH} = \frac{\lambda \tau_H (2\lambda - 1) (2(\lambda - 1) - \tau_H (2\lambda - 1))}{(\lambda - 1) (4\lambda - 1)^2} \\ \bar{\phi}^{FH} &= \pi_1^{FH} - \pi_1^{HH} = \frac{\tau_H (2\lambda - 1) (4\lambda (\lambda - 1) + \tau_H)}{(\lambda - 1) (4\lambda - 1)^2} \end{aligned}$$

Both firms relocate if  $\phi < \phi^{FF} = \frac{\lambda \tau_H (2\lambda - 1) (2(\lambda - 1) - \tau_H (2\lambda - 1))}{(\lambda - 1) (4\lambda - 1)^2}$ .

### Environmental Policy

If both firms remain in  $H$  (equilibrium  $HH$ ), the welfare-maximizing tax rate is

$$\tau_H^{HH} = \frac{(2\lambda + 7) \lambda}{(\lambda + 1) (8\lambda + 1)}.$$

If the high-quality firm relocates to  $F$  and the low-quality firm remains in  $H$ , the welfare-maximizing tax rate is

$$\tau_H^{FH} = \begin{cases} \frac{(\lambda - 1)(4\lambda - 2\lambda^2 - 1)}{\lambda(-9\lambda + 8\lambda^2 + 2)} & \text{if } \lambda < \frac{1}{2}\sqrt{2} + 1 \\ 0 & \text{if } \lambda \geq \frac{1}{2}\sqrt{2} + 1 \end{cases}.$$