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Pollution, Pigouvian Taxes, and Asymmetric International Oligopoly*

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Résumé / Abstract

Nous obtenons des règles de taxation sur la pollution qui tiennent compte de l'argument sur la redistribution des rentes, du besoin d'éviter la pollution transfrontalière, de la correction pour le volume insuffisant de l'output d'un oligopole, et de la correction pour le manque de coordination entre les firmes domestiques. Nous montrons que la libéralisation du commerce mondial n'entraîne pas nécessairement une augmentation du niveau de pollution.

We derive emission tax rules that take into account (i) the rent-shifting argument, (ii) the need to mitigate transboundary pollution, (iii) correction for restrictive oligopoly output, and (iv) correction for domestic coordination of outputs. We show that trade liberalization does not necessarily result in more pollution.

Mots Clés : Pollution, oligopole, libéralisation du commerce mondial

Keywords : Pollution, oligopoly, trade liberalization

JEL : L13, F13

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1 Introduction

The on-going efforts of governments to achieve multilaral trade liberalization have not been universally welcome. Environmentalists often express the fear that an increased volume of trade will lead to more pollution and further degradation of natural resources such as forests and waterways. Industrialists in advanced economies worry that, with the reduction in tariffs, there will be increased competition from firms operating in less developed countries, where laxed environmental standards imply that these firms incur relatively lower costs. Powerful pressure groups in advanced economies often ask their governments to penalize imports of goods originating from countries which have laxer environmental or labour standards. Less developed countries have also been accused of not enforcing environmental and labour standards, so as to enable its local firms to achieved a "comparative advantage" in the global market, and also to attract foreign capital. Some authors have expressed the concern that there is a "race to the bottom", which would in the end harm everyone. On the other hand, as put by Anderson (1995), "developing countries perceive the entwining of these social issues with trade policy as a threat to both their sovereignty and their economies."

In this paper we consider a model of oligopolistic trade when governments adopt policies that affect both trade and the environment. An important feature of our model is the assumption that firms are not identical, and that governments can adopt discriminatory (i.e., firm-specific) taxes or standards. While firm-specific taxes on outputs or on quantities exported (or imported) are not popular and not often encountered in practice (partly because of international agreements or conventions, such as the "Most Favoured Nation" principle), firm-specific taxes on emissions seem to be gaining acceptance, because they are seen as measures to internalize environmental externalities which, by their nature, are specific to a production environment.

Optimal Pigouvian taxes under oligopoly has been studied by Katsoulacos and Xepapadeas (1995) under the assumption that firms are identical. They show that if the number of firms is exogenous, then the optimal emission tax falls short of the marginal damage cost (because, in the absence of externality, oligopoly output is below the socially efficient level). This result is an extension of the monopoly case[1]. On the other hand, if the number of firms is endogenous and if there are fixed costs, they obtain the conclusion that the optimal Pigouvian tax could exceed the marginal damage cost. In their model, effluent fees serve to

[1]For Pigouvian tax under monopoly, see Buchanan (1969) and Barnett (1980), among others.

"correct" outputs (and emissions) when there are two sources of market failure: market power and environmental damages.

Matters become more complicated when the polluting oligopoly consists of domestic firms producing in the home country and foreign rivals producing in the foreign countries. From the publications by Ulph (1992), Barrett (1994), Conrad (1996a, b), and Rauscher (1994, 1997), four factors have been identified that affect deviations of optimal emission taxes from marginal damage costs[2]. Firstly, there is the rent shifting argument: taxes can shift rents from foreign firms to domestic firms. Secondly, one should not neglect the need to mitigate transboundary pollution from foreign producers. Thirdly, output of an oligopoly tends to be too low relative to consumer benefits. Fourthly, when there are several domestic firms, oligopolistic behaviour does not minimize the production cost of a given volume of domestic output. In the literature, specific models have developed models to address some of these issues, but not all four issues simultaneously. Ulph (1996) has a model with the first three factors present but where there is one one firm in each country, though these firms can have different costs. Barrett (1994) and Kennedy (1995) allow for many firms in each country, but these firms are identical. A main contribution of our paper is that it integrates all the factors within a model where firms are not identical. We consider the case where firms are **heterogeneous** both in production costs, and in emission per unit of output. We allow the governments to use firm-specific emission taxes.

In Section 3, we consider the case where two governments set emission taxes non-cooperatively. We show that at the Nash equilibrium in the game between the two governments, the firm-specific emission tax rates on larger firms are smaller than average. If domestic firms are identical and there is no pollution spillover, then the domestic emission tax is greater [respectively, smaller] than the marginal environmental damage provided that the number of domestic firms is sufficiently great [respectively, small] relative to the number of foreign firms. However, if foreign pollution has spillover effects on the home country, then domestic emission tax may be smaller than the marginal environmental damage even when the number of domestic firms is great.

In Section 4 we turn to the analysis of the effect of trade liberalization on emission taxes. We assume that the foreign country imposes no emission or trade taxes, while the home country initially imposes both emission taxes and import tariffs. We examine whether a reduction in import tariffs (trade liberalisation) lead to lower emission taxes

[2]See also the survey chapters by Ulph in Folmer and Tietenberg (1997/1998).

and higher domestic emissions.We show that if the weight given to consumers' surplus is zero, then under certain conditions, a partial trade liberalization will lead to a countervailing reduction in emission taxes that leave total emission in the home country unchanged. However, if the weight given to consumers' surplus is sufficiently great, then a partial trade liberalization will lead to significant reductions in domestic emission taxes, and more domestic emission.

2 A Model of Asymmetric Oligopoly

Consider an international Cournot oligopoly consisting of n non-identical firms, of which m_H are in the home country (country H), and m_F are in the foreign country (country F). The firms produce a homogenous good. Firms differ from each other in two respects: (a) production cost, and (b) emission per unit of output. In each country, the government sets emission tax rates that can be firm-specific.

Let x_i denote firm i's output.The cost of producing x_i is $\alpha_i c(x_i)$ where $\alpha_i > 0$ is a parameter and $c(.)$ is a convex and increasing function, with $c(0) = 0$. Its emission of pollutant is $e_i = \epsilon_i x_i$, where $\epsilon_i > 0$ is firm-specific constant. Firm i faces a firm-specific tax t_i per unit of emission, or, equivalently

$$\tau_i = \epsilon_i t_i \tag{1}$$

per unit of output. Here we assume that in each country the government can charge discriminatory emission taxes.

The firms sell their output in the same market. (This market can be an integrated world market, or the home country's market, or the foreign country's market, or a market in a third country). Let $H = \{1, 2, ..., m_H\}$ and $F = \{m_H + 1, ..., n\}$. The demand function is represented by $P = P(X)$ where $X = X_H + X_F$ and

$$X_H \equiv \sum_{h \in H} x_h, \quad X_F \equiv \sum_{f \in F} x_f$$

We assume that $P'(X) < 0$, $P(0) > 0$,and that there exists $\bar{X}$ such that $P(\bar{X}) = 0$. In addition, we will need the assumption that

$$(n+1)P'(X) + XP''(X) < 0 \tag{2}$$

This condition is satisfied if the marginal revenue curve for the industry has a negative slope.[3]

[3]For a complete set of assumptions that guarantees existence and uniqueness of Cournot equilibrium, see Gaudet and Salant (1991). We will take it that they hold in our model.

The home country's welfare is the sum of the home consumers' surplus, home producers' surplus, government's tax revenue, less pollution damages.

We first ask the following question: suppose that Country F has set the emission tax rates $(t_{m_H+1}, ..., t_n)$, what is Country H's best responses in terms of its own firm-specific emission taxes? To answer this question, it is convenient to show that choosing home emission tax rates are equivalent to choosing directly home firms' outputs, subject to the constraints that firms' outputs are consistent with a Cournot equilibrium. To see this, let us begin with the first order condition for firm k:

$$P'(\hat{X})\hat{x}_k + P(\hat{X}) = \alpha_k c'(\hat{x}_k) + \tau_k \tag{3}$$

This equation determines a relationship

$$\hat{x}_k = \phi_k(\hat{X}, \tau_k) \equiv \phi_k(\hat{X}_F + \hat{X}_H, \tau_k) \tag{4}$$

that must hold between the industry's *equilibrium* output $\hat{X}$ and firm k's *equilibrium* output $\hat{x}_k$. Note that $\phi_{kX} \equiv \partial\phi_k(\hat{X}, \tau_k)/\partial\hat{X} < 0$ under the assumption that $P''(\hat{X})\hat{x}_k + P'(\hat{X}) < 0$, and $\phi_{k\tau} \equiv \partial\phi_k(\hat{X}, \tau_k)/\partial\tau_k < 0$.

Thus the equilibrium output produced in country F is

$$\hat{X}_F = \sum_{f \in F} \phi_f(\hat{X}_F + \hat{X}_H, \tau_f) \tag{5}$$

This yields

$$\hat{X}_F = \hat{X}_F(\hat{X}_H, \tau_{\mathbf{F}}) \tag{6}$$

where by definition $\tau_{\mathbf{F}} \equiv (\tau_{\mathbf{m_H+1}}, ..., \tau_{\mathbf{n}})$, and where

$$\frac{\partial\hat{X}_F}{\partial\hat{X}_H} = \frac{\sum_{f \in F} \phi_{fX}}{1 - \sum_{f \in F} \phi_{fX}} < 0 \tag{7}$$

Equation (6) means that, given $\tau_{\mathbf{F}}$, if the home country can control the aggregate output of the home oligopolists, then the aggregate output of the foreign oligopolists is uniquely determined.

Since, in equilibrium, $\hat{X}_H + \hat{X}_F = \hat{X}$, it follows that

$$\hat{X} = \hat{X}_H + \hat{X}_F(\hat{X}_H, \tau_{\mathbf{F}}) = \hat{\mathbf{X}}(\hat{\mathbf{X}}_{\mathbf{H}}, \tau_{\mathbf{F}}) \tag{8}$$

and

$$\frac{\partial\hat{X}}{\partial\hat{X}_H} = \frac{1}{1 - \sum_{f \in F} \phi_{fX}} > 0$$

To illustrate, consider the special case with a linear demand $P(Q) = A - BQ$, and quadratic costs $\alpha_k c(x_k) = (\alpha_k/2)x_k^2$. Then in equilibrium

$$\hat{x}_f = \gamma_f[(A - \tau_f) - B\hat{X}_H - B\hat{X}_F] \tag{9}$$

where $\gamma_f \equiv 1/(B + \alpha_f)$. Let

$$\gamma_F \equiv \frac{1}{m_F} \sum_{f \in F} \gamma_f \tag{10}$$

Then

$$\hat{X}_F(\hat{X}_H, \tau_\mathbf{F}) = \frac{\mathbf{A m_F \gamma_F}}{\mathbf{1 + B m_F \gamma_F}} - \frac{\sum_{\mathbf{f \in F}} \tau_\mathbf{f} \gamma_\mathbf{f}}{\mathbf{1 + B m_F \gamma_F}} - \frac{\mathbf{B m_F \gamma_F}}{\mathbf{1 + B m_F \gamma_F}} \hat{\mathbf{X}}_\mathbf{H} \tag{11}$$

and

$$\hat{X}(\hat{X}_H, \tau_\mathbf{F}) = \frac{\mathbf{1}}{\mathbf{1 + B m_F \gamma_F}} \left[\mathbf{A m_F \gamma_F} - \sum_{\mathbf{f \in F}} \tau_\mathbf{f} \gamma_\mathbf{f} + \hat{\mathbf{X}}_\mathbf{H} \right] \tag{12}$$

Thus, for a given $\tau_\mathbf{F}$, the home government can choose $\hat{X}_H$ and the $\hat{x}_h$, $h \in H$, and generate a Cournot equilibrium, supporting it by a suitably chosen vector $\tau_\mathbf{H}$ so that (3) is satisfied.

We now derive an expression for the welfare of the home country. The aggregate emission by firms in country H is $E_H = \sum_{h \in H} \epsilon_h x_h = \sum_{h \in H} e_h$. Similarly, the aggregate emission by foreign firms is $E_F = \sum_{f \in F} \epsilon_f x_f$. Assume that the home country's valuation of total damage is $D(E_H + \sigma_F E_F)$ where σ_F is the spillover coefficient from foreign pollution to the home country, $1 \geq \sigma_F \geq 0$. Let $\hat{X}$ denote the Cournot equilibrium output. Define consumers' surplus as

$$S(\hat{X}) = \int_0^{\hat{X}} P(X) dX - \hat{X} P(\hat{X})$$

Social welfare in the home country is defined as a weighted sum of consumers' surplus, home firms' profit, and government's revenue from emission taxes, less pollution damage (for the moment, we assume there are no tariffs for simplicity)

$$\hat{W}_H = \beta_H S(\hat{X}) + \sum_{h \in H} \hat{\pi}_h + \sum_{h \in H} t_h e_h - D_H(E_H + \sigma_F E_F) \tag{13}$$

where $\hat{\pi}_h$ is firm h's equilibrium profit, and where $\beta_H \geq 0$ is the weight given to consumers' surplus ($\beta_H = 0$ if the good is not sold in the home market.)

In what follows, we assume that $D(.)$ is linear function, with $D'_H = \delta_H > 0$.Using the definition (1) and (3), we can express $\hat{W}_H$ (13) in a Cournot equilibrium as

$$\hat{W}_H = \beta_H \hat{S} + \hat{X}_H \hat{P} - \sum_{h \in H} \psi_h(\hat{x}_h) - \delta_H \sigma_F E_F \tag{14}$$

where

$$\psi_h(\hat{x}_h) \equiv \delta_H \epsilon_h \hat{x}_h + \alpha_h c(\hat{x}_h)$$

where $\hat{x}_h$ is firm h's *equilibrium* output, $\hat{X}$ is *equilibrium* industry output, $\hat{S} = S(\hat{X})$, and $\hat{P}$ is the *equilibrium* price.

3 Non-cooperative Pigouvian Taxes

In this section, we seek answers to the following questions: (i) Given a set of emission taxes imposed by a foreign country, what are the home country's optimal emission taxes, under the assumption that the home country cannot vary its trade taxes, and (ii) if both countries try to optimize (non-cooperatively) by setting firm-specific emission taxes, what is the resulting Nash equilibrium?

We assume that the cost function $c(x)$ is *strictly convex.* The following proposition characterize the optimal emission taxes in the home country, for a *given* vector of emission taxes in the foreign country:

Proposition 3.1: (Optimal firm-specific Pigouvian taxes)

Given the foreign choice of $\tau_{\mathbf{F}}$, the optimal firm-specific Pigouvian tax per unit of emission by firm h is given by

$$t_h = \delta_H + \frac{1}{\epsilon_h}[-\hat{P}']\hat{X}_H \left[\left(A_H - \frac{\beta_H \hat{X}}{\hat{X}_H} \right) \left(\frac{\partial \hat{X}}{\partial \hat{X}_H} \right) - \frac{\hat{x}_h}{\hat{X}_H} \right], \text{for all } h \in H \tag{15}$$

where $\hat{X}_H$ is the home industry output, and

$$A_H \equiv 1 + \frac{\delta_H \sigma_F}{[-P']\hat{X}_H} \sum_{f \in F} \epsilon_f \frac{\partial \hat{x}_f}{\partial \hat{X}} \tag{16}$$

Thus (i) t_h is greater, the greater is the damage cost δ_H,(ii) t_h is negatively related to the weight β_H attached to consumers' surplus, and (iii) in equilibrium, among all firms that have the same ϵ_h, smaller firms pay higher tax rates per unit of emission (This is because small firms are those which have high α_h, they are less efficient, and the optimal policy seeks to reduce their outputs.)

Proof: See the Appendix.

Remark 3.1: Consider first the case where $\beta_H = 0$, that is, the good is not sold in the home market. Proposition 3.1 indicates that emission tax t_h is equal to marginal environmental damage (δ_H) plus an adjustment factor. This factor is zero if the export price of the good, $\hat{P}$, is exogenous. In the case of an oligopoly, $\hat{P}$ is not exogenous. If there is no spillover from foreign pollution (i.e., if $\sigma_F = 0$) then $A_H = 1$ and the tax formula (15) becomes

$$t_h = \delta_H + \frac{1}{\epsilon_h}[-\hat{P}']\hat{X}_H \left[\frac{\partial \hat{X}}{\partial \hat{X}_H} - \hat{s}_h \right]$$

where $\hat{s}_h = \hat{x}_h / \hat{X}_H$. Then t_h is smaller than the damage cost δ_H if and only if $\hat{s}_h > \partial \hat{X} / \partial \hat{X}_H$. If, in addition, all domestic firms are identical (implying $\hat{s}_h = 1/m_H$) then t_h is smaller than the marginal damage cost δ_H if and only if the number of domestic firms is sufficiently small:

$$\frac{\partial \hat{X}}{\partial \hat{X}_H} < \frac{1}{m_H} \tag{17}$$

In this case the shortfall of t_h over δ_H reflects the desire of the home government to expand domestic output so as to capture a bigger market share. If $\sigma_F = 0$ and $\partial \hat{X} / \partial \hat{X}_H = 1/m_H$, then $t_h = \delta_H$ Condition (17) can also be expressed in terms of the slopes of foreign firms' reaction functions

However, if spillover is present (i.e., $\sigma_F > 0$), and $\partial \hat{x}_f / \partial \hat{X} < 0$ (see Example 1 above) then $A_H < 1$ and hence it is possible that $t_h < \delta_H$ even if $\partial \hat{X} / \partial \hat{X}_H > 1/m_H$ (i.e., even if the home firms are numerous). The reason for this is as follows: by reducing emission tax rates below the marginal environmental damage δ_H, the home country 's output $\hat{X}_H$ will expand, and this will reduce foreign output and hence foreign emission (which is harmful to the home country).

Remark 3.2: If $\beta_H > 0$ (the good is sold in the home country) and if $\sigma_F = 0$ (no spillover from foreign pollution) then (15) reduces to

$$t_h = \delta_H + \frac{1}{\epsilon_h}[-\hat{P}']\hat{X}_H \left[\{1 - [\beta_H \hat{X} / \hat{X}_H]\} \partial \hat{X} / \partial \hat{X}_H - \hat{s}_h \right]$$

In particular, if there are no foreign firms, then firm h will be taxed at a rate below the marginal damage δ_H if and only if its output share is greater than $1 - \beta_H$.

We now turn to the task of characterizing a Nash equilibrium emission taxes when both countries try to maximize national welfare.

Proposition 3.2: (Nash equilibrium firm-specific Pigouvian taxes)

If both countries set firm-specific Pigouvian taxes in response to each other, then the Nash equilibrium taxes in the game between the two countries are given by

$$t_h = \delta_H + \frac{1}{\epsilon_h}[-P']\hat{X}_H \left[\left(A_H - \frac{\beta_H \hat{X}}{\hat{X}_H} \right) \frac{\partial X}{\partial X_H} - \frac{\hat{x}_h}{\hat{X}_H} \right] \text{ for all } h \in H \tag{18}$$

and

$$t_f = \delta_F + \frac{1}{\epsilon_f}[-P']\hat{X}_F \left[\left(A_F - \frac{\beta_F \hat{X}}{\hat{X}_F} \right) \frac{\partial X}{\partial X_H} - \frac{\hat{x}_f}{\hat{X}_F} \right] \text{ for all } f \in F \tag{19}$$

where A_H is given by (16) and A_F is defined in a similar way.

Example 3.1

With linear demand $P = 1 - X$ and quadratic cost $c(x) = (1/2)x^2$, conditions (18) and (19) give

$$\tau_h = a_h + b_h \hat{X} + \frac{1}{1-\gamma_h} \sum_{f \in F} \eta_f \tau_f \quad , h \in H \tag{20}$$

$$\tau_f = a_f + b_f \hat{X} + \frac{1}{1-\gamma_f} \sum_{h \in H} \eta_h \tau_h \quad , f \in F \tag{21}$$

where

$$a_h \equiv \frac{1}{1-\gamma_h} \left[(\epsilon_h \delta_H - \gamma_h) - \frac{1}{1+m_F \gamma_F} \sum_{f \in F} \gamma_f (1 + \sigma_F \delta_H \epsilon_f) \right] , h \in H$$

$$a_f \equiv \frac{1}{1-\gamma_f} \left[(\epsilon_f \delta_F - \gamma_f) - \frac{1}{1+m_H \gamma_H} \sum_{h \in H} \gamma_h (1 + \sigma_H \delta_F \epsilon_h) \right] , f \in F$$

$$b_h \equiv \frac{1}{1-\gamma_h} \left(\gamma_h + \frac{1 - \beta_H + m_F \gamma_F}{1 + m_F \gamma_F} \right) , h \in H$$

$$b_f \equiv \frac{1}{1-\gamma_f} \left(\gamma_f + \frac{1 - \beta_F + m_H \gamma_H}{1 + m_H \gamma_H} \right) , f \in F$$

$$\eta_h \equiv \frac{\gamma_h}{1 + m_F \gamma_F} \quad , h \in H$$

$$\eta_f \equiv \frac{\gamma_f}{1 + m_H \gamma_H} \quad , f \in F$$

Furthermore, recall that from (11)

$$\hat{X}_F = \sum_{f\in F} \gamma_f(1-\tau_f) - m_F\gamma_F\hat{X}$$

and similarly

$$\hat{X}_H = \sum_{h\in H} \gamma_h(1-\tau_h) - m_H\gamma_H\hat{X}$$

Hence the equilibrium output is

$$\hat{X} = \frac{1}{1+m_F\gamma_F+m_H\gamma_H}\left[\sum_{f\in F}\gamma_f(1-\tau_f) + \sum_{h\in H}\gamma_h(1-\tau_h)\right] \tag{22}$$

Substituting (22) into (20) and (21) we obtain n linear equations in τ_h and τ_f, and the Nash equilibrium taxes are uniquely determined.

4 Effects of Trade Liberalization on the Environment

In this section, we examine the effects of trade liberalization on the quality of the environment under the assumptions that the polluting industry is an international oligopoly, and that the home government can adjust emission taxes in response to a required reduction in tariff rates (demanded by an international body, such as the World Trade Organization).

We use the model developed in the preceding section, and consider the case where the goods are sold only in the home market. We assume that the foreign government does not impose any tax (nor subsidy) on output (nor on emissions). The home country already has in place a set of import tariffs on the good produced by the foreign oligopolists. We assume that these tariff rates are exogenously set[4] (for example they might be controlled by international bodies such as the World Trade Organization). Given these tariff rates, the home government has as policy instruments firm-specific emission taxes on home firms. These instruments are optimally set to maximize home welfare. We seek the

[4]The case where the tariff rates are not exogenously set is considered briefly in the Appendix. There, we show that even if tariff rates are optimally set, the optimal emission taxes still deviate from the marginal damage cost. This is because, of the four factors mentioned in the introduction, tariffs deal only with the first two.

answers to the following questions: suppose that due to a new international agreement, all import tariffs must be cut by a given amount, how would the home government adjust its emission taxes? Would the adjustment result in a lower quality of the environment?

The home welfare function is the sum of W_H defined in the preceding section, and tariff revenue:

$$W_H^0 = W_H + \sum_{f \in F} T_f x_f$$

where T_f is the import tariff on foreign firm f's good. (Here, we allow firm-specific tariff, but the special case where all T_f are required to be identical is admitted.)

The relationship between the Cournot equilibrium industry output $\hat{X}$ and firm f 's equilibrium output is $\hat{x}_f = \hat{x}_f(\hat{X}, T_f)$, where T_f now takes the place of τ_f. It is convenient to define $\bar{\epsilon}_f(T_f)$ as follows

$$\sigma_F \delta_H \bar{\epsilon}_f(T_f) = \sigma_F \delta_H \epsilon_f - T_f \tag{23}$$

Then we obtain

$$W_H^0 = X_H \hat{P} + \beta_H \hat{S} - \sum_{h \in H} \psi_h(\hat{x}_h) - \sigma_F \delta_H \sum_{f \in F} \bar{\epsilon}_f \hat{x}_f$$

and we can apply the analysis of the problem of maximizing W_H in the previous section to the problem of maximizing W_H^0 of this section. We thus obtain the following optimal emission tax formulas, for exogenously given tariff rates T_f:

$$t_h = \delta_H + \frac{1}{\epsilon_h}[-\hat{P}']\hat{X}_H \left[\left(\bar{A}_H - \frac{\beta_H \hat{X}}{\hat{X}_H} \right) \left(\frac{\partial \hat{X}}{\partial \hat{X}_H} \right) - \frac{\hat{x}_h}{\hat{X}_H} \right] \tag{24}$$

where

$$\bar{A}_H \equiv 1 + \frac{\sigma_F \delta_H}{[-\hat{P}']\hat{X}_H} \sum_{f \in F} \bar{\epsilon}_f \frac{\partial \hat{x}_f}{\partial \hat{X}}$$

We are now ready to determine whether an exogenous reduction in the import tariff rates (i.e., a marginal trade liberalization) would lead to a reduction in emission taxes. To simplify computation, we specialize in the case where the demand function is linear and the cost function $c(x)$ is quadratic. Then we obtain the following proposition:

Proposition 4.1:

(i) If the weight given to consumers' surplus is zero ($\beta_H = 0$), then, with linear demand and quadratic cost, a partial trade liberalization (i.e., a reduction, but not necessarily elimination, of all tariffs) would lead to a reduction in emission taxes in the home country. However, the output (and hence emission) of each home firm will remain **unchanged**. As a result, foreign output and pollution will rise.

(ii) If the weight given to consumers' surplus is positive ($\beta_H > 0$), then, with linear demand and quadratic cost, a partial trade liberalization would lead to (a) a reduction in emission taxes in the home country, and (b) an **increase** in the output (and emission) of each domestic firm.

Proof: See the Appendix

Part (i) of Proposition 4.1 shows that the claim made by some environmentalists that trade liberalization would lead to more pollution in the home country is not always correct. This result is rather special, and one may suspect that it depends on the assumption that pollution is directly proportional to output. If there is scope for abatement activities, the equivalence between an emission tax and an output tax is broken, and thus when emission taxes are reduced to offset the impact on domestic output of a lowering of import tariffs, the level of domestic emission may rise.

5 Concluding Remarks:

In this paper, we studied the properties of equilibrium Pigouvian taxes when these have impacts on international trade. The firm-specific optimal emission taxes were derived. These taxes were shown to exceed or fall short of the marginal environmental damages, depending on the numbers of home and foreign firms, and on their cost characteristics.We also showed that trade liberalization need not always result in a more polluted environment.

One aspect of pollution reduction that we did not deal with in this paper is the re-location of plants. This is the subject matter of a companion paper. We have also assumed that pollution is a flow rather than a stock which evolves over time. Designing emission taxes for polluting oligopolists in a model with accumulation of the pollution stock has been studied by Benchekroun and Long (1998) in the context of a closed economy. It would seem worthwhile to extend their model to the case of an international oligopoly

Appendix

Proof of Proposition 3.1

$\hat{W}_H$ can be expressed as

$$\hat{W}_H = \beta_H S(\hat{X}) + \hat{X}_H \hat{P} - \sum_{h \in H} \psi_h(\hat{x}_h) - \sigma_F \delta_H \sum_{f \in F} \epsilon_f \hat{x}_f \qquad (25)$$

Since $\hat{x}_f = \phi_f(\hat{X}, \tau_f)$ for all foreign firms, and Country H seeks to maximize (25) by choosing firm-specific emission tax $t_h = \tau_h / \epsilon_h$ ($h = 1, ..., m_H$), given the foreign vector $\tau_{\mathbf{F}}$. In view of (3), (6), and (8), this maximization problem is equivalent to maximizing (25) by choosing *directly* both the home industry output $\hat{X}_H$, and the vector $(\hat{x}_1, ..., \hat{x}_{m_H})$ of outputs of the home firms, subject to the constraint

$$\sum_{h \in H} \hat{x}_h = \hat{X}_H \qquad (26)$$

(Afterwards, we can infer the emission taxes from (3).) It is convenient to solve this problem in two steps. In the first step, we take $\hat{X}_H$ as given, (and hence $\hat{X}$ and $\hat{P}$ as given), and maximize with respect to $(\hat{x}_1, ..., \hat{x}_{m_H})$, subject to (26). In the second step, we choose $\hat{X}_H$.

The first step:

For a given $\hat{X}_H$, maximization of (25) subject to (26) involves setting up the Lagrangian

$$L_H = G(\hat{X}_H, \lambda_H) + \sum_{h \in H} [\lambda_H \hat{x}_h - \psi_h(\hat{x}_h)] \qquad (27)$$

where

$$G(\hat{X}_H, \lambda_H) \equiv \beta_H S(\hat{X}) + \{\hat{P} - \lambda_H\} \hat{X}_H - \sigma_F \delta_H \sum_{f \in F} \epsilon_f \hat{x}_f(\hat{X}, \tau_f) \qquad (28)$$

Differentiating with respect to $\hat{x}_h$, we obtain the first order conditions which say that the full marginal cost of output (production cost plus environmental damage) must be equalized across all home firms:

$$\delta_H \epsilon_h + \alpha_h c'(\hat{x}_h) = \lambda_H \qquad (29)$$

or

$$\hat{x}_h = c'^{-1} \left(\frac{\lambda_H - \delta_H \epsilon_h}{\alpha_h} \right) \qquad (30)$$

This implies that among firms with identical ϵ_h , firms with high α_i produce less. From (30) we get

$$\hat{x}_h = \hat{x}_h(\lambda_H) \qquad (31)$$

Summing (31) over all all $h \in H$, we get

$$\sum_{h \in H} \hat{x}_h(\lambda_H) = \hat{X}_H \tag{32}$$

Since $\hat{x}_h(\lambda_H)$ is strictly increasing in λ_H, equation (32) uniquely determines the optimal λ_H, for given $\hat{X}_H : \hat{\lambda}_H = \hat{\lambda}_H(\hat{X}_H)$.

To illustrate our approach, consider the following example:

Example

With linear demand $P = 1 - Q$ and quadratic cost $\alpha_i c(x_i) = (\alpha_i/2)x_i^2$, we get

$$\hat{x}_h(\lambda_H) = \frac{[\lambda_H - \delta_H \epsilon_h]}{\alpha_h}$$

and hence (32) gives

$$\hat{\lambda}_H = v_H \rho_H + v_H \hat{X}_H$$

where $\rho_H \equiv \delta_H \sum_{h \in H}[\epsilon_h/\alpha_h]$ and $v_H \equiv 1/\sum_{h \in H}[1/\alpha_h]$. **(End of example)**

The second step

We now determine the optimal $\hat{X}_H$. We follow the duality methods used in Rockafellar (1970)[5]. Following Rockafellar, we define the conjugate functions

$$\psi_h^*(\lambda_H) \equiv \max_{x_h}\{\lambda_H \hat{x}_h - \psi_h(\hat{x}_h)\}$$

then, for a given $\hat{X}_H$, the value of the Lagrangian $\hat{L}$ (optimized with respect to the $\hat{x}_h$'s) is

$$\hat{L} = \beta_H S(\hat{X}) + \hat{X}_H\{P(\hat{X}) - \hat{\lambda}_H(\hat{X}_H)\} + \\ \sum_{h \in H} \psi_h^*(\hat{\lambda}_H(\hat{X}_H)) - \sigma_F \delta_H \sum_{f \in F} \epsilon_f \hat{x}_f(\hat{X}, \tau_f) \tag{33}$$

Here, $\hat{L}$ depends only on $\hat{X}_H$ (to be chosen in the second step) and on the foreign tax vector $\tau_{\mathbf{F}}$ chosen by the foreign government.

We now differentiate (33) with respect to $\hat{X}_H$ and equate it to zero:

$$[\hat{P}']\{\hat{X}_H - \beta_H \hat{X}\}\frac{\partial \hat{X}}{\partial \hat{X}_H} + \hat{P} - \hat{\lambda}_H(\hat{X}_H) - \sigma_F \delta_H \sum_{f \in F} \epsilon_f \frac{\partial \hat{x}_f}{\partial \hat{X}} \frac{\partial \hat{X}}{\partial \hat{X}_H} = 0 \tag{34}$$

[5] See Rockafellar (1970, Theorem 28.4 and Corollary 28.4.1., pp 284-5); see also Luenberger (1969, Theorem 1, p. 224)

(in deriving this equation, we have used the facts that $\frac{d\psi_h^*}{d\lambda_H} = \hat{x}_h$). If $\hat{L}(\hat{X}_H)$ is concave and the solution is interior, then equation (34) determines country H's unique optimal choice of $\hat{X}_H$ for given $\tau_{\mathbf{F}}$.

From the equilibrium condition for firm h (see (3) and (1)), we have $\epsilon_h t_h = \hat{x}_h \hat{P}' + \hat{P} - \alpha_h c'(\hat{x}_h)$ and using (29), we get $\epsilon_h t_h = \hat{x}_h \hat{P}' + \delta_H \epsilon_h + [\hat{P} - \lambda_H]$. Use (34) to substitute for $[\hat{P} - \lambda_H]$.□

Proof of Proposition 4.1

We make use of (9) to (12), with $A = B = 1$ for simplicity, where τ_f is now replaced by the tariff T_f imposed by country H on goods imported from country F. We have

$$\hat{x}_f = \gamma_f[(1 - T_f) - \hat{X}]$$

$$\hat{X}_F = -m_F \gamma_F \hat{X} + \sum_{f \in F} \gamma_f (1 - T_f) \equiv \hat{X}_F(\hat{X}, \mathbf{T_F})$$

where $\gamma_F \equiv (1/m_F) \sum_{f \in F} \gamma_f$, and, since in equilibrium $\hat{X}_H = \hat{X} - \hat{X}_F(\hat{X}, \mathbf{T_F})$, we must have

$$\hat{X}_H = (1 + m_F \gamma_F)\hat{X} - \sum_{f \in F} \gamma_f (1 - T_f) \equiv J\hat{X} - K \tag{35}$$

where $J = 1 + m_F \gamma_F$ and $K = \sum_{f \in F} \gamma_f (1 - T_f)$. Hence

$$\frac{\partial \hat{X}_H}{\partial \hat{X}} = 1 + m_F \gamma_F \equiv J$$

Recall that the first order condition of the maximization of L with respect to x_h, where $h \in H$, is

$$\hat{x}_h = \frac{\lambda_H - \delta_H \epsilon_h}{\alpha_h} \tag{36}$$

or

$$\hat{x}_h = [a_h \lambda_H - \delta_H b_h] \quad , h \in H \tag{37}$$

where $a_h \equiv 1/\alpha_h$ and $b_h \equiv \epsilon_h/\alpha_h$. Summing over all $h \in H$ yields

$$\hat{X}_H = m_H a_H \lambda_H - m_H b_h \delta_H \tag{38}$$

where $a_H \equiv (1/m_H) \sum_{h \in H} a_h$ and $b_H \equiv (1/m_H) \sum_{h \in H} b_h$. Finally, from (34)

$$P(X) - \lambda_H = \frac{\hat{X}_H - \beta_H \hat{X} - \delta_F \sum_{f \in F} \bar{\epsilon}_f \gamma_f}{J} \tag{39}$$

The three equations (35),(38), and (39) determine $\lambda_H, \hat{X}$, and $\hat{X}_H$. Solving for λ_H:

$$\lambda_H = \frac{J^2 - KJ + 2Jm_H b_H + \beta_H K + \sigma_F \delta_H J \sum_{f\in F} \bar{\epsilon}_f \gamma_f}{[2J - \beta_H] m_H a_H + J^2} \tag{40}$$

Now let trade liberalization be represented by a small reduction in all T_f. Write $T_f = T_f^0 - u$. Then, from (40), and recalling that K and $\bar{\epsilon}_f$ are functions of the T_f's, the effect of a marginal trade liberalization on λ_H is

$$\frac{\partial \lambda_H}{\partial u} = \frac{\beta_H \gamma_F m_F}{[2J - \beta_H] m_H a_H + J^2} \geq 0 \tag{41}$$

(where we assume $2 \geq \beta_H$) and hence, using (37)

$$\frac{\partial \hat{x}_h}{\partial u} = \frac{a_h \beta_H \gamma_F m_F}{[2J - \beta_H] m_H a_H + J^2} \geq 0 \tag{42}$$

and thus the total domestic emission increases:

$$\frac{\partial E_H}{\partial u} = \frac{\beta_H \gamma_F m_F}{[2J - \beta_H] m_H a_H + J^2} \sum_{h\in H} \epsilon_h a_h$$

Also,

$$\frac{\partial \hat{X}_H}{\partial u} = \frac{m_F a_H \beta_H \gamma_F}{[2J - \beta_H] m_H a_H J + J^2} \geq 0$$

From (35) $\hat{X} = (K + \hat{X}_H)/J$, hence

$$\frac{\partial \hat{X}}{\partial u} = \frac{1}{J}\left(\gamma_F m_F + \frac{m_F a_F \beta_H \gamma_F}{[2J - \beta_H] m_F a_F + J^2}\right) > 0$$

Now, the equilibrium condition for home firms is

$$\epsilon_h t_h = \hat{x}_h P' + P(\hat{X}) - \alpha_h c'(\hat{x}_h)$$

therefore

$$\epsilon_h \frac{\partial t_h}{\partial u} = -\frac{\partial \hat{x}_h}{\partial u} - \frac{\partial \hat{X}}{\partial u} - (\alpha_h)\frac{\partial \hat{x}_h}{\partial u} < 0$$

Optimal tariffs and optimal emission taxes:

In Section 4, it was assumed that the tariff rates are exogenously set. We now modify the model by allowing for the choice of tariff rates. We wish to find out whether the optimal emission taxes still deviate from marginal damage cost when tariffs are optimally chosen. Maximizing W_H^0 with respect to the tariff rates T_f , $f \in F$, and bearing in mind

(23), we obtain m_F equations that determine the optimal firm-specific tariff rates, for a given $\hat{X}_H$

$$[\hat{P}']\{\hat{X}_H - \beta_H \hat{X}\}\frac{\partial \hat{X}}{\partial T_f} + \hat{x}_f - \sigma_F \delta_H \sum_{j\in F} \bar{\epsilon}_j \frac{\partial \hat{x}_j}{\partial \hat{X}}\frac{\partial \hat{X}}{\partial T_f} = 0, \quad f \in F \quad (43)$$

The optimal choice of $\hat{X}_H$ must satisfy a condition similar to(34):

$$[\hat{P}']\{\hat{X}_H - \beta_H \hat{X}\}\frac{\partial \hat{X}}{\partial \hat{X}_H} + \hat{P} - \hat{\lambda}_H(\hat{X}_H) - \sigma_F \delta_H \sum_{j\in F} \bar{\epsilon}_j \frac{\partial \hat{x}_j}{\partial \hat{X}}\frac{\partial \hat{X}}{\partial \hat{X}_H} = 0 \quad (44)$$

To illustrate, consider the special case where there is only one foreign firm, and the inverse demand function is $P = 1 - X$, and the cost function is $\alpha_f c(x_f) = (\alpha_f/2)x_f^2$, with $\alpha_f = 1$, so that $\gamma_f = 1/2$. Assume $\beta_H = 1$. Then (43) gives

$$T_f - \sigma_F \delta_H \epsilon_f = \frac{1}{\gamma_f}\hat{x}_f = \frac{1}{1+\gamma_f}\left[1 - T_f - \hat{X}_H\right] \quad (45)$$

Hence

$$T_f = \frac{\gamma_f}{2+\gamma_f}\left[\sigma_F \delta_H + \left(\frac{\gamma_f}{1+\gamma_f}\right)\left(1 - \hat{X}_H\right)\right] \quad (46)$$

which is positive since $\hat{X}_H \leq X \leq 1$ given that $P = 1 - X \geq 0$. Finally, substituting (46) into (24), we obtain the optimal emission taxes:

$$t_h = \delta_H - \frac{\hat{x}_h}{\epsilon_h} < \delta_H$$

This shows that under linear demand and quadratic costs, when the tariff rates are optimally chosen, the optimal emission taxes will fall short of the marginal damage cost.

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