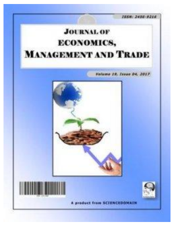

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Oligopolistic Competition, Asymmetric Trade and Pollution Taxes

Salvador Sandoval Bravo[1*] and Víctor Hugo Gualajara Estrada[1]

[1]Department of Quantitative Methods, University of Guadalajara, University Center of Economic and Administrative Sciences, Periférico Norte799, Núcleo Universitario Los Belenes, ZC.45100, Zapopan, Jalisco, México.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This study develops a partial equilibrium model for asymmetric trade between two heterogeneous companies located in different countries under reciprocal dumping and oligopolistic competition conditions. All governments must implement a series of strategic environmental policies with the objective of maximizing the wellbeing of the country, considering company utility, consumer benefit, government income obtained through the levying of pollution taxes, and the social cost of polluting. It can be determined that, if the disutility of polluting is considerably high, governments should levy taxes on pollution. On the other hand, they could also opt not to tax pollution, provided that there is compliance with certain additional conditions that depend on other related parameters, such as marginal production costs and the scale of the companies' production.

Keywords: Pollution tax; asymmetric trade competition; oligopoly; environmental policies.

1. INTRODUCTION

The intensive use of natural resources, further to the continual growth in production and the manufacture of goods and services, causes the emission of pollutants into the environment. Pollution is both the direct and indirect cause of a great number of adverse effects to the

**Corresponding author: E-mail: alvador.sandoval@academicos.udg.mx;*

environment, such as acid rain, the greenhouse effect, global warming, and the increase in the incidence and severity of hurricanes and tropical storms, which, moreover, cause losses amounting to millions for nations' economies.[1] Furthermore, a lot of respiratory, auditory, visual and intestinal diseases in people are caused by pollutants in the environment, with a resulting increase in the costs to public health [1].

For this reason, governments implement a series of regulatory measures that limit pollution levels and guarantee a healthy environment. In this sense, these regulatory measures are considered trade barriers, given that companies incur additional costs when reducing their emissions, representing an increase in their production costs and thus reducing their competitiveness. This subject, involving economic development, international trade and sustainability, has been widely debated in various global forums – those dealing with both trade and the environment – over the last 30 years.[2] Thus, governments face the great challenge of maintaining a healthy environment for their inhabitants, while, at the same time, guaranteeing competitiveness for their companies and the economic development of their nations.

Among others, the following must be considered in the context of international negotiations over the environmental controls imposed on companies: cost-benefit analysis for the chosen instruments (as these will determine the application of environmental policy); cost structure; company heterogeneity; and, the size of the countries involved. These relative differences in the size of the companies and the countries that are affected could influence not only the negotiation process but also the impact that pollution could have on production and trade, in terms of the benefit for both companies and people's health. Thus, in the global context, pollution controls represent a trade distortion, which affects trade among countries, both quantitatively and qualitatively, as well as their general welfare, which includes both their companies and their inhabitants.

Although there are many studies on environmental regulations,[3] not enough studies have been conducted on the rubric for environmental controls and commercial competition. Thus, this study approaches the subject of the establishment of strategic environmental policies through, specifically, the implementation of an environmental control instrument, a pollution tax, and its effects on the trade relationships between different-sized countries, in both of which there is a heterogeneous company trading a homogeneous good.

Governments use pollution taxes as an instrument to regulate the pollution emitted through companies' production processes, an instrument which will also be used in this study. The ideas underlying pollution tax are *who pollutes pays* and *who pollutes more pays more*. From this perspective, it is an efficient pollution control instrument, given that, if the companies seek to reduce their environmental costs, they must reduce their emissions, either by investing in clean technologies or improving their manufacturing processes. The establishment of optimal pollution taxes requires knowledge of the companies' cost structure and the calculation of the potential damages that pollution could cause to both the environment and people's health. In this way, a pollution tax is an effective tool from an economic perspective, given that it enables the reduction of the pollution produced by companies, independent of the level of pollution. Furthermore, being the product of a government collection instrument, the sums collected are transferred, in part, into public investment.

International trade between two countries with similar goods is known as intra-industrial trade.[4] This bidirectional exchange of similar, if not identical, merchandise is also known in international economic literature as *cross-hauling*. It has been widely analyzed in the specialized bibliography dealing with price-

[1] [2] They estimate average losses of around 17,000 million dollars per year due to tornados, hurricanes and floods over the 1955-2006 period, solely in the United States, which, in some years has surpassed the 100,000 million dollar mark. Similarly, according to Mohleji and Pielke [3], global losses under this rubric increased to an average of more than 3,000 million dollars between 1980 and 2008. They also state how 97% of these costs correspond to damages centered on North America, Europe, Asia and Australia, with losses in North America representing 57% of global losses.

[2] Among which can be mentioned the Rio de Janeiro Conference in 2012, the Kyoto Protocol in 1999, the Johannesburg and Paris summits of 2002 and 2015, respectively, and both the General Agreement on Tariffs and Trade (GATT) and the World Trade Organization (WTO) trade agreements that include entire chapters on the control of pollution caused by the process of producing goods and services.

[3] For example, the meticulous study by Cropper and Oates [4].

[4] Among the classic studies on intra-industrial trade, the following can be cited [5,6,7].

setting in perfect competition, although some studies have been conducted in the context of imperfect markets, particularly under Cournot's framework of oligopoly.

Thus, [8,9] conclude that competition in the trade of homogenous goods between oligopolistic companies could naturally generate bidirectional international trade of the same good. The specific case of intra-industrial trade is known as reciprocal dumping. Reciprocal dumping between the two countries is possible due to the fact that the markets are segmented, with the companies taking different business decisions in terms of their production for both local consumption and exportation. Generally, they set different prices for the same article – a high price for the local market and a lower price for the foreign market, as this provides ideal trading conditions. Moreover, constant returns to scale and no significant comparative advantages are found, while the companies' cost structures are different. In theory, this could increase the companies' competitiveness by inducing a reduction of prices in both countries for the benefit of consumers. Thus, reciprocal trade in a good between two countries will be considered an important assumption for this study.

This study will thus develop a partial equilibrium model between two heterogeneous companies (in that they feature different cost structures) in distinct countries and under reciprocal dumping conditions, in order to determine the optimal pollution tax for the trade in a homogeneous good. This optimal tax will be calculated under both the cooperative and non-cooperative frameworks, while the strategic environmental policy will be deduced based on the optimal values for the pollution tax. This policy will maximize the general welfare function of the countries, which includes both the benefits for the companies, the consumer surplus, government revenue through pollution tax collection, and the social cost of pollution.

The model is described in Section 2, below. The calculations for the optimal pollution tax in the non-cooperative environment are shown in Section 3, and the optimal pollution tax under the cooperative framework is calculated in Section 4, while Section 5 presents the study's final conclusions.

2. THE MODEL

The model supposes the existence of two countries (*A* and *B*) which trade a homogeneous good with each other [10,11]. A partial equilibrium model is developed in an oligopolistic environment, in which *n* identical companies operate in Country *A* and *m* identical companies operate in Country *B*. The companies in the two countries maximize their production quotas while taking the output of other firms as given.

This study assumes that labor is the unique production factor in each country. It is also assumed that labor provision in country *B*, l_B, is higher than labor provision in country *A*, l_A, for which reason Country *B* is considered the larger and Country *A* the smaller. The total production factor in the two countries can be normalized in such a way that $l_A + l_B = 1$. According to Markusen and Venables [12], labor is inelastic in an environment of perfect competition and with constant returns to scale, in such a way that its price is considered numeraire.

X and *Y* represent the total quantity of goods produced by each company in Country *A* and Country *B*, respectively. However, $X = X_A + X_B$, where X_A and X_B represent production for local consumption and exportation for each company in Country *A*. Similarly, $Y = Y_A + Y_B$, where Y_B and Y_A represent production for local consumption and exportation for each company in Country *B*.

K_A are K_B are denoted as the marginal costs for countries *A* and *B*, respectively, which can be considered constant and equal to the average of their variable costs.[5] The marginal production costs have two components, the first being the technological component that depends on market conditions and the second being the term associated with the costs incurred due to the application of environmental policy by the government (to be detailed later in this paper). Furthermore, a transport cost, *t*, can be considered for exported goods and is distributed among the exporting companies. It is assumed that the markets are separated or segmented, with inverse quasilinear utility functions also assumed in such a way that:

$$U(P_A, \mu_A) = \frac{\beta l_A P_A^2}{2} - \delta_A l_A P_A + \mu_A \quad (1)$$

$$U(P_B, \mu_B) = \frac{\beta l_B P_B^2}{2} - \delta_B l_B P_B + \mu_B \quad (2)$$

Where P_A and P_B are the prices in countries *A* and *B*, respectively, while μ_A and μ_B represent

[5] *The existence of a numeraire good produced in a market of perfect competition can be taken as implicit.*

the consumption of numeraire goods in both countries; finally, δ_A,δ_B and β are the positive constants of the linear demand equation. Using Roy's identity, the demand equations are deduced in the two countries, which are linear in relation to the price. Without considering the income effect, the following is obtained:

$$D_A = l_A(\delta_A - \beta P_A) \tag{3}$$

$$D_B = l_B(\delta_B - \beta P_B) \tag{4}$$

Where,

$$D_A = nX_A + mY_A \tag{5}$$

$$D_B = mY_B + nX_B \tag{6}$$

Using equations (3), (4), (5) and (6) obtains the inverse functions for demand in countries *A* and *B*, respectively.

$$P_A = a_A - \frac{b}{l_A} D_A \tag{7}$$

$$P_B = a_B - \frac{b}{l_B} D_B \tag{8}$$

where, $b = 1/\beta$, $a_A = \delta_A/\beta$ and $a_B = \delta_B/\beta$.

Thus, the utility of each company in countries *A* and *B* is given by:

$$\Pi_A = (P_A - K_A)X_A + (P_B - K_A - t)X_B \tag{9}$$

$$\Pi_B = (P_B - K_B)X_B + (P_A - K_B - t)X_A \tag{10}$$

The companies in each country decide the amount allocated for the local and export markets. According to the Nash-Cournot assumptions, the first order conditions that maximize the utility function for each company can be obtained:[6]

$$a_A - K_A = b(n+1)X_A - bmY_A \tag{11}$$

$$a_B - K_A - t = b(n+1)X_B - bmY_B \tag{12}$$

$$a_B - K_B = b(m+1)Y_B - bnX_B \tag{13}$$

$$a_A - K_B - t = b(m+1)Y_A - bnX_A \tag{14}$$

However, given that demand is linear, the second order maximization conditions are satisfied:[7]

$$\Pi_A = bX_A^2 + bX_B^2 \tag{15}$$

$$\Pi_B = bX_B^2 + bX_A^2 \tag{16}$$

Using (15) and (16) and resolving the systems for separable simultaneous equations, namely (11) and (14) and (12) and (13), obtains the equilibrium quantities for reciprocal trade for each company in countries *A* and *B*:

$$Y_A = l_A \frac{(n+1)(a_A - K_B - t) - n(a_A - K_A)}{b(m+n+1)} \tag{17}$$

$$X_A = l_A \frac{(m+1)(a_A - K_A) - m(a_A - K_B - t)}{b(m+n+1)} \tag{18}$$

$$X_B = l_B \frac{(m+1)(a_B - K_A - t) - m(a_B - K_B)}{b(m+n+1)} \tag{19}$$

$$Y_B = l_B \frac{(n+1)(a_B - K_B) - n(a_B - K_A - t)}{b(m+n+1)} \tag{20}$$

The general wellbeing for countries *A* and *B* are defined, including the application of the regulatory instrument for environmental policy, in the following manner:

$$W_A = n\Pi_A + CS_A + \tau_A Z_A - \psi Z_A \tag{21}$$

$$W_B = m\Pi_B + CS_B + \tau_B Z_B - \psi Z_B \tag{22}$$

Where $n\Pi_A$ and $m\Pi_B$ in (21) and (22) represent the benefits for local companies in countries *A* and *B* respectively. Similarly, CS_A and CS_B are the consumer surplus for countries *A* and *B*, and are specified in equations (23) and (24). The social cost of polluting in countries *A* and *B* is expressed by $\psi_A Z_A$ and $\psi_B Z_B$, respectively. Z_A and Z_B represent the quantity of pollutants emitted by the respective countries *A* and *B*, and are defined by $Z_A = nz_A X$ and $Z_B = mz_B Y$, where z_A and z_B are the quantity of polluting emissions per unit of the homogeneous good. Moreover, ψ represents the marginal disutility of polluting that, according to Lahiri and Ono [13], Markusen et al. [14], Markusen et al. [15], can be assumed as a constant.[8] For the purposes of simplicity, it can

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[6] Substituting (5) and (6) in (7) and (8), respectively, and subsequently these new expressions of P_A and P_B in (9) and (10), respectively. Finally, the derivatives $\frac{d\Pi_A}{dX_A} = 0$, $\frac{d\Pi_A}{dX_B} = 0$, $\frac{d\Pi_B}{dX_A} = 0$ and $\frac{d\Pi_B}{dX_B} = 0$ are computed, which generate equations (11-14).

[7] Using (11), (7) and (5) we obtain $X_A = b(P_A - K_A)$; from (12), (8) and (6) we get $X_B = b(P_B - K_A - t)$; from (13), (8) and (6) we obtain $X_B = b(P_B - K_B)$; and from (14), (7) and (5) we get $X_A = b(P_A - K_B - t)$. And by replacing these expressions in (9) and (10) we have (15) and (16).

[8] Authors such as [16] consider that the value of ψ is increasing and depends on the quantity of the good produced.

be also assumed that the damage caused by pollution is the same in both countries, given that, exceptions aside, the adverse effects caused to people by pollution is similar. Finally, $\tau_A Z_A$ and $\tau_B Z_B$ represent the amount in pollution taxes collected by the governments of countries *A* and *B*, respectively, while τ_A and τ_B denote the per unit pollution tax levied on the companies by the respective countries *A* and *B*. Thus, the tax is the instrument of environmental regulation used by the government to control pollution.[9]

$$CS_A = bD_A^2/2 \tag{23}$$

$$CS_B = bD_B^2/2 \tag{24}$$

3. OPTIMUM POLLUTION TAX IN THE NON-COOPERATIVE ENVIRONMENT

Given the specification of the model, the optimal tax is calculated in the context of the cooperative environment and the policies derived from it. For this reason, this study uses the pollution tax as an instrument of pollution control, in which the companies are charged a sum per unit of pollution emitted during their production processes. The marginal production cost for countries *A* and *B*, respectively, is thus defined as:

$$K_A = C_A + T_A \quad \text{and} \quad K_B = C_B + T_B \tag{25}$$

Where C_A and C_B correspond to the technological component that depends on the market conditions. They mainly include raw materials and inputs used in the manufacturing of goods, and can be considered constants. Furthermore, the terms T_A and T_B represent the costs incurred due to the application of the environmental policy by the government, which is defined, according to Sandoval [11], as:[10]

$$T_A = \gamma(\theta - z_A) + \tau_A z_A \quad \text{and} \quad T_B = \gamma(\theta - z_B) + \tau_B z_B \tag{26}$$

θ can be denoted as the amount of pollutants emitted per unit of the good, prior to the application of the pollution tax as a regulatory measure. Thus θX and θY represent the total amount of pollutants emitted per company in countries *A* and *B*, respectively. Similarly, $n\theta X$ and $m\theta Y$ represent the total amount of pollutants emitted in countries *A* and *B* by companies *n* and *m*, respectively. z_A and z_B are the amounts of pollution emitted per unit of product subsequent to the companies' application of their environmental policy, considering that they are able to pay less tax by reducing their emissions, given that that they have access to adequate technology for reducing the pollution caused by their production processes.[11]

λ is the abatement cost, namely the cost to the company of reducing each unit of pollution emitted, which this study considers to be the same in both countries. According to (25) and (26), the marginal cost of production for the companies in countries *A* and *B* is given by:

$$K_A = C_A + \lambda(\theta - z_A) + \tau_A z_A \text{ and } K_B = C_B + \lambda(\theta - z_B) + \tau_B z_B \tag{27}$$

Intuitively, it is clear that, when the abatement cost is higher than the pollution tax, the companies prefer to pay the tax, while, if the pollution tax is higher than the abatement cost, the companies will opt not to pollute. This can be expressed as follows:

$$z_A = \begin{cases} 0 \; si \; \tau_A \geq \lambda \\ \theta \; si \; \tau_A < \lambda \end{cases} \quad \text{and} \quad z_B = \begin{cases} 0 \; si \; \tau_B \geq \lambda \\ \theta \; si \; \tau_B < \lambda \end{cases} \tag{28}$$

therefore,

$$K_A = \begin{cases} C_A + \lambda\theta & si \; \tau_A \geq \lambda \\ C_A + \tau_A\theta & si \; \tau_A < \lambda \end{cases} \text{ and } K_B = \begin{cases} C_B + \lambda\theta & si \; \tau_B \geq \lambda \\ C_B + \tau_B\theta & si \; \tau_B < \lambda \end{cases} \tag{29}$$

$$Z_A = \begin{cases} 0 & si \; \tau_A \geq \lambda \\ nX_A\theta + nX_B\theta & si \; \tau_A < \lambda \end{cases} \text{ and } Z_B = \begin{cases} 0 & si \; \tau_B \geq \lambda \\ mY_A\theta + mY_B\theta & si \; \tau_B < \lambda \end{cases} \tag{30}$$

It is clear that the calculation of the optimal pollution tax only makes sense when it is lower than the abatement cost $\tau_A < \lambda$ and $\tau_B < \lambda$, given that, when $\tau_A \geq \lambda$ and $\tau_B \geq \lambda$, the total level of emissions is zero, according to (30).

Differentiating (17) - (20) and using (29), we obtain:

$$dX_A = -\frac{l_A\theta(m+1)}{b\alpha}d\tau_A + \frac{l_A m\theta}{b\alpha}d\tau_B \tag{31}$$

[9]*For a wider discussion about pollution taxes see [17].*
[10]*For the purposes of simplicity, θ and γ are the same both countries.*

[11]*Both θ and z_A and z_B are considered higher than the level evaluated by the WHO as not harmful.*

$$dX_B = -\frac{l_B\theta(m+1)}{b\alpha}d\tau_A + \frac{l_B m\theta}{b\alpha}d\tau_B \quad (32)$$

$$dY_A = -\frac{l_A\theta(n+1)}{b\alpha}d\tau_B + \frac{l_A\theta n}{b\alpha}d\tau_A \quad (33)$$

$$dY_B = -\frac{l_B\theta(n+1)}{b\alpha}d\tau_B + \frac{l_B\theta n}{b\alpha}d\tau_A \quad (34)$$

in such a way that $\alpha = m + n + 1$.

Applying (5) and (6) using (31) – (34) gives the total differential of demand:

$$dD_A = -\frac{l_A\theta n}{b\alpha}d\tau_A - \frac{l_A\theta m}{b\alpha}d\tau_B \quad (35)$$

$$dD_B = -\frac{l_B\theta m}{b\alpha}d\tau_B - \frac{l_B\theta n}{b\alpha}d\tau_A \quad (36)$$

Using (35) and (36), as well as (23) and (24), obtains the total differential of consumer surplus:

$$dCS_A = -\frac{l_A D_A\theta n}{\alpha}d\tau_A - \frac{l_A D_A\theta m}{\alpha}d\tau_B \quad (37)$$

$$dCS_B = -\frac{l_B D_B\theta m}{\alpha}d\tau_B - \frac{l_B D_B\theta n}{\alpha}d\tau_A \quad (38)$$

Analyzing the impact of pollution taxes on the consumer surplus, from (37) and (38), leads to the conclusion that, when pollution taxes are increased, the consumer surplus decreases, given that the marginal production costs increase, which directly influences the price of the goods available to consumers. On the contrary, reducing the level of taxes increases consumer surplus.

Using (15) and (16), and (31) - (34) again, enables the calculation of the total differential of the benefit of the companies, thus:

$$d\Pi_A = -\frac{2\theta(m+1)(X_A l_A + X_B l_B)}{\alpha}d\tau_A + \frac{2m\theta(X_A l_A + X_B l_B)}{\alpha}d\tau_B \quad (39)$$

$$d\Pi_B = -\frac{2\theta(n+1)(Y_A l_A + Y_B l_B)}{\alpha}d\tau_B + \frac{2m\theta(Y_A l_A + Y_B l_B)}{\alpha}d\tau_A \quad (40)$$

Examining the effect of pollution taxes on the benefit for companies, as taken from (39) and (40), leads to the observation that reducing the pollution taxes in the local country favors the competitiveness of the local companies over foreign companies by reducing the marginal production costs in the local country. This will increase the benefit for local companies, while the benefit to the foreign companies will decrease.

Using (30) when $\tau_A, \tau_B < \lambda$, and using (31) – (34) again, obtains the total differential of government income from the levying of pollution taxes on companies, from which the following is obtained:

$$d(\tau_A Z_A) = \left(-\tau_A\frac{n\theta^2(m+1)}{b\alpha} + n\theta X\right)d\tau_A + \left(\tau_A\frac{mn\theta^2}{b\alpha}\right)d\tau_B \quad (41)$$

$$d(\tau_B Z_B) = \left(-\tau_B\frac{m\theta^2(n+1)}{b\alpha} + m\theta Y\right)d\tau_B + \left(\tau_B\frac{mn\theta^2}{b\alpha}\right)d\tau_A \quad (42)$$

Studying the impact of pollution taxes in $\tau_A Z_A$ and $\tau_B Z_B$, from (41) and (42), leads to the observation that, when the government increases pollution taxes, tax revenue increases. However, this also raises marginal production costs, thus disincentivizing production and decreasing income from pollution taxes. In this sense, the aggregate effect is uncertain.

Finally, using (30) when $\tau_A, \tau_B < \lambda$, and using (31) – (34) again, obtains the total differential of social cost of polluting, from which gives the following:

$$dZ_A = -\frac{n\theta^2(m+1)}{b\alpha}d\tau_A + \frac{mn\theta^2}{b\alpha}d\tau_B \quad (43)$$

$$dZ_B = -\frac{m\theta^2(n+1)}{b\alpha}d\tau_B + \frac{mn\theta^2}{b\alpha}d\tau_A \quad (44)$$

Thus, an analysis of the effect of the application of environmental policy on the social cost of polluting, using (43) and (44), reveals that increasing pollution taxes in the local country increases marginal production costs. This disfavour the companies' levels of production and, therefore, reduces the emission of pollutants into the environment and the social costs of polluting. However, this does increase the competitiveness and productivity of foreign companies, thus increasing emissions in the foreign company. It can also be observed that the size of the countries has no effect on the impact of the implementation of pollution taxes on the social cost of polluting.

From (37) - (44), the total differential of (21) and (22) with respect to the pollution tax policy can be obtained in the following expressions:

$$dW_A = E_1 d\tau_A + E_2 d\tau_B \quad (45)$$

$$dW_B = E_3 d\tau_B + E_4 d\tau_A \quad (46)$$

Where

$$E_1 = n\theta\alpha^{-1}[-l_A D_A - 2(m+1)(X_A l_A + X_B l_B) + X\alpha + \theta b^{-1}(\psi - \tau_A)(m+1)]$$
$$E_2 = \theta m\alpha^{-1}[-l_A D_A - 2n(X_A l_A + X_B l_B) - n\theta b^{-1}(\psi - \tau_A)]$$
$$E_3 = \theta m\alpha^{-1}[-l_B D_B - 2(n+1)(Y_A l_A + Y_B l_B) + Y\alpha + \theta b^{-1}(\psi - \tau_B)(n+1)]$$
$$E_4 = \theta n\alpha^{-1}[-l_B D_B - 2m(Y_A l_A + Y_B l_B) - m\theta b^{-1}(\psi - \tau_B)]$$

The first term within the square brackets in (45) and (46) is the consumer surplus effect, which is clearly negative for any pollution tax in both countries, given that an increase in the tax will increase marginal production costs and, consequently, reduce the amount of the good produced, thus increasing the price for consumers.

The second term found within the square brackets in (45) and (46) is the producer surplus effect. Along with the increase in pollution tax in a local country, the cost for the local companies increases, while the producer surplus decreases. The cost disadvantage for local companies reduces their competitiveness with foreign companies, while the producer surplus of foreign companies increases.

Finally, the remaining terms in the square brackets in (45) and (46) represent the damaging effect of pollution. When less pollution is permitted in a local country through the imposition of the pollution tax, the cost to the company located in this country increases and production decreases; therefore, local wellbeing increases because this has a positive impact on human health. On the other hand, this tax would increase the foreign companies' competitiveness and levels of production, which, in turn, would increase the amount of pollution emitted in the foreign country. The ambiguous effect of tax revenue is also manifested in these same terms, given that, on the one hand, the implementation of the pollution tax increases government income; however, on the other hand, both the production costs and the final price for consumers increase.

The concavity conditions establish that:

$$\frac{d^2W_A}{d\tau_A^2} = \frac{n\theta^2}{b\alpha^2}\Big(2(l_A^2 + l_B^2)(m+1)^2 + \big(nl_A^2 - 2\alpha(m+1)\big)\Big) < 0 \tag{47}$$

$$\frac{d^2W_B}{d\tau_B^2} = \frac{m\theta^2}{b\alpha^2}\Big(2(l_A^2 + l_B^2)(n+1)^2 + \big(ml_B^2 - 2\alpha(n+1)\big)\Big) < 0 \tag{48}$$

The first factor in (47) and (48) is clearly positive; moreover, considering that $l_A + l_B = 1$, it can be easily shown that:

$$2(l_A^2 + l_B^2)(m+1)^2 + \big(nl_A^2 - 2\alpha(m+1)\big) < 0$$
$$2(l_A^2 + l_B^2)(n+1)^2 + \big(ml_B^2 - 2\alpha(n+1)\big) < 0$$

which implies that W_A and W_B, are concave.

To find the optimal values in the non-cooperative equilibrium, the following is required:

$\frac{dW_A}{d\tau_A} = 0$ and $\frac{dW_B}{d\tau_B} = 0$.

from which the following equations are obtained:

$$\frac{dW_A}{d\tau_A} = -\frac{l_A D_A \theta n}{\alpha} - n\frac{2\theta(m+1)(X_A l_A + X_B l_B)}{\alpha} - \tau_A\frac{n\theta^2(m+1)}{b\alpha} + n\theta X + \psi\frac{n\theta^2(m+1)}{b\alpha} = 0 \tag{49}$$

$$\frac{dW_B}{d\tau_B} = -\frac{l_B D_B \theta m}{\alpha} - m\frac{2\theta(n+1)(Y_A l_A + Y_B l_B)}{\alpha} - \tau_B\frac{m\theta^2(n+1)}{b\alpha} + m\theta Y + \psi\frac{m\theta^2(n+1)}{b\alpha} = 0 \tag{50}$$

From the above expressions, the optimal pollution taxes in the non-cooperative equilibrium can be deduced:

$$\tau_A^*\frac{\theta(m+1)}{b} = X_A\big(\alpha - l_A(2m+n+2)\big) + X_B\big(\alpha - 2l_B(m+1)\big) - mY_A l_A + \psi\frac{\theta(m+1)}{b} \tag{51}$$

$$\tau_B^*\frac{\theta(n+1)}{b} = Y_B\big(\alpha - l_B(2n+m+2)\big) + Y_A\big(\alpha - 2l_A(n+1)\big) - nX_B l_B + \psi\frac{\theta(n+1)}{b} \tag{52}$$

From this point on, this study assumes a monopoly in each country, which means that $m = n = 1$. This hypothesis will simplify the analysis without affecting the use of the principal variables. In the event that the size of the countries is very different, in such a way that $l_A \ll l_B$, $l_A \to 0$ and $l_B \to 1$, the following is obtained from (51) and (52):

$$\tau_A^*\frac{2\theta}{b} = 3X_A - X_B + \psi\frac{2\theta}{b} \tag{53}$$

$$\tau_B^*\frac{2\theta}{b} = -2Y_B - X_B + 3Y_A + \psi\frac{2\theta}{b} \tag{54}$$

Given (53) and (54), it can be observed that when ψ is significantly large, $\tau_A^*, \tau_B^* > 0$. This conclusion is clear, with the government placing a much higher value on the adverse effects of pollution when the costs associated with it are very high, while, at the same time, being stimulated to increase its tax revenue. On the other hand, the benefits for the companies decrease, as does the consumer surplus, due to the increase in the marginal production cost and the resulting increase in prices for the consumer. Moreover, it is clear that $\frac{d\tau_A^*}{d\psi}, \frac{d\tau_B^*}{d\psi} > 0$, therefore, the higher marginal disutility for polluting, the greater the tax applied by the government. It can be formally summarized in the following proposition.

Proposition 1. In the non-cooperative equilibrium, if $l_A \to 0$, and $l_B \to 1$

If ψ is sufficiently high, then $\tau_A^* > 0$ and $\tau_B^* > 0$

Alternatively, in the event that both countries are of a similar size, in that $l_A \approx l_B \approx 0.5$, the optimal pollution tax would be:

$$\tau_A^* \frac{2\theta}{b} = 0.5X_A + X_B - 0.5Y_A + \psi \frac{2\theta}{b} \tag{55}$$

$$\tau_B^* \frac{2\theta}{b} = 0.5Y_B + Y_A - 0.5X_B + \psi \frac{2\theta}{b} \tag{56}$$

Formulas (55) and (56) can be interpreted via the following proposition.

Proposition 2. In the non-cooperative equilibrium, if $l_A \approx l_B \approx 0.5$

1. If ψ is sufficiently high, then $\tau_A^* > 0$ and $\tau_B^* > 0$
2. If $Y_A \gg X_B$, then $\tau_A^* = 0$, and if $X_B \gg Y_A$, then $\tau_B^* = 0$

The first result for the above proposition expresses the fact that the government applies a positive tax, provided that the disutility of polluting is considerably high, thus placing more value on the potential negative effect of pollution on human health than on the other components of the function of wellbeing.

However, there is a very clear intuitive interpretation for the second result of the previous proposition. If the quantity of goods imported is considerably higher than the quantity of goods exported, the best policy is a zero tax rate. In this case, the government favors the local companies by reducing their costs, which positively influences their benefits and increases their competitiveness compared to foreign companies. At the same time, this benefits consumers, who pay lower prices as a consequence of the reduction of the marginal cost.

Optimal environmental policy for non-cooperative equilibrium can be summarized in the following terms. If the marginal disutility of polluting is sufficiently high, the government applies a positive tax, for both small and large countries ($l_A \to 0$, and $l_B \to 1$) and similar-sized countries ($l_A \approx l_B \approx 0.5$). In this case, the adverse effect on human health as caused by pollution is taken more into account than the other components of wellbeing in these countries.

4. POLLUTION TAX IN THE COOPERATIVE ENVIRONMENT

With the optimal environmental policies determined above, the pollution control policies in a cooperative environment will be analyzed below. This study considers that Country *A* will establish the optimal tax, τ_A^*, taking into account the impact of this policy on not only its own wellbeing, but also the wellbeing of Country *B*. Similarly, τ_B^* will also be obtained. Formally, based on (45) and (46), the following is obtained:

$$dW_A = (E_1 + E_4)d\tau_A \tag{57}$$

$$dW_B = (E_2 + E_3)d\tau_B \tag{58}$$

Developing and simplifying (57) and (58), in order that $H_1 = l_AX_A + l_BX_B$ and $H_2 = l_AY_A + l_BY_B$, the following is obtained:

$$\begin{aligned} dW_A = n\theta\alpha^{-1}\big(&-l_A(nX_A + mY_A) - 2(m+1)H_1 + (X_A + X_B)\alpha + \theta b^{-1}(m+1)(\psi - \tau_A) - l_B(mY_B + nX_B) \\ &+ 2mH_2 - m\theta b^{-1}(\psi - \tau_B)\big)d\tau_A \end{aligned}$$

$$\begin{aligned} dW_B = m\theta\alpha^{-1}\big(&-l_B(mY_B + nX_B) - 2(n+1)H_2 + (Y_A + Y_B)\alpha + \theta b^{-1}(n+1)(\psi - \tau_B) - l_A(nX_A + mY_A) \\ &+ 2nH_1 - n\theta b^{-1}(\psi - \tau_A)\big)d\tau_B \end{aligned}$$

Simplifying even further, considering that $m = n = 1$, the following is obtained:

$$dW_A = \frac{1}{3}\theta\left(2H_2 - 4H_1 + 3X_A + 3X_B - l_A(X_A + Y_A) - l_B(X_B + Y_B) - \frac{1}{b}\theta(\psi - \tau_B) + \frac{2}{b}\theta(\psi - \tau_A)\right)$$

$$dW_B = \frac{1}{3}\theta\left(2H_1 - 4H_2 + 3Y_A + 3Y_B - l_A(X_A + Y_A) - l_B(X_B + Y_B) - \frac{1}{b}\theta(\psi - \tau_A) + \frac{2}{b}\theta(\psi - \tau_B)\right)$$

Setting $dW_A = 0$ and $dW_B = 0$ and solving the system of simultaneous equations for τ_A and τ_B obtains the optimal policies for pollution taxes:

$$\tau_A^* = \frac{1}{\theta}(-3bH_1 - bH_2 + 2bX_A + 2bX_B + bY_A + bY_B + \theta\psi) \tag{59}$$

$$\tau_B^* = \frac{1}{\theta}(-3bH_2 - bH_1 + 2bY_B + 2bY_A + bX_A + bX_B + \theta\psi) \tag{60}$$

Firstly, analyzing the asymmetric case ($l_A \to 0$ and $l_B \to 1$), (59) and (60) are transformed into:

$$\tau_A^* = \frac{1}{\theta}(-bX_A + 2bX_B + bY_B + \theta\psi) \tag{61}$$

$$\tau_B^* = \frac{1}{\theta}(-bY_B + 2bY_A + bX_A + \theta\psi) \tag{62}$$

The result from the two previous equations can be formally expressed as:

Proposition 3. In the cooperative equilibrium, if $\boldsymbol{l_A \to 0}$***, and*** $\boldsymbol{l_B \to 1}$

If $\boldsymbol{\psi \gg 0}$***, then*** $\boldsymbol{\tau_A^* > 0}$ ***and*** $\boldsymbol{\tau_B^* > 0}$

Similarly, in the above propositions signifies that, when the social cost of polluting is significantly high, governments act to protect the environment and people's health at the expense of the benefits for the companies and the consumer surplus.

However, when the countries are of a similar size ($l_A \approx l_B \approx 0.5$), (59) and (60) are transformed into:

$$\tau_A^* = \psi + \frac{b(X_A + X_B + Y_A + Y_B)}{2\theta} \tag{63}$$

$$\tau_B^* = \psi + \frac{b(X_A + X_B + Y_A + Y_B)}{2\theta} \tag{64}$$

from the interpretation of which, the following proposition can be formulated:

Proposition 4. In cooperative equilibrium, if $\boldsymbol{l_A \approx l_B \approx 0.5}$***, then*** $\boldsymbol{\tau_A^* = \tau_B^* > 0}$

The previous proposition indicates that, for similar-sized countries with the monopoly for a good in both countries, their governments will always apply a tax which will increase or decrease according to fluctuations in the marginal disutility of polluting, thus controlling emissions through the tax in a coordinated manner with the variations in the social cost of polluting. However, this intra-government application of environmental policy also involves the companies' production quotas. While the quantity of goods produced by the companies may be higher or lower, governments will attempt to control emissions either by increasing or decreasing the respective pollution tax by the same measure, thus attempting to give equal weight to the environmental damage in both countries without overly affecting the benefits to both the companies and the final consumer.

Finally, it should be noted that the function W_A is not continuous in $\tau_A = \lambda$, given the manner in which K_A is defined in (29). Thus, using limits from (28), (29) and (30) leads to the following:

$$lim_{\tau_A \to \lambda^+} W_A = CS_A + n\Pi_A^* + \tau_A Z_A - \psi Z_A \quad (65)$$

$$lim_{t_A \to \lambda^+} W_A = CS_A + n\Pi_A^* \quad (66)$$

$$lim_{\tau_A \to \lambda^-} W_A = CS_A + n\Pi_A^* + \tau_A Z_A - \psi Z_A \quad (67)$$

$$lim_{\tau_A \to \lambda^-} W_A = CS_A + n\Pi_A^* + \lambda(nX_A\theta + nX_B\theta) - \phi(nX_A\theta + nX_B\theta) \quad (68)$$

$$lim_{\tau_A \to \lambda^-} W_A = CS_A + n\Pi_A^* + (\lambda - \psi)(nX_A\theta + nX_B\theta) \quad (69)$$

Using (66) and (69), gives:

$$lim_{\tau_A \to \lambda^+} W_A - lim_{\tau_A \to \lambda^-} W_A = (\psi - \lambda)(nX_A\theta + nX_B\theta) \quad (70)$$

while, from (70), the following can be deduced:

$$lim_{\tau_A \to \lambda^+} W_A - lim_{\tau_A \to \lambda^-} W_A > 0 \;\; si\; \psi > \lambda \quad (71)$$

$$lim_{\tau_A \to \lambda^+} W_A - lim_{\tau_A \to \lambda^-} W_A = 0 \;\; si\; \psi = \lambda \quad (72)$$

$$lim_{\tau_A \to \lambda^+} W_A - lim_{\tau_A \to \lambda^-} W_A < 0 \;\; si\; \psi < \lambda \quad (73)$$

The same reasoning can be repeated by analyzing the discontinuity of W_B in $\tau_B = \lambda$, and stating the following proposition:

Proposition 5. For both the cooperative and non-cooperative environment

1. If $\psi \geq \lambda$ then $\tau_A^* \geq \lambda$ and $\tau_B^* \geq \lambda$, thus the companies do not pollute.
2. If $\psi < \lambda$ then $\tau_A^* < \lambda$ and $\tau_B^* < \lambda$, thus the companies do not reduce the pollution emitted.

Intuitively, if the marginal disutility of polluting is higher than the abatement cost, the pollution tax is also higher than the abatement cost. For this reason, it is more convenient, for the companies, to assume the cost of abating the pollution than to pay the corresponding tax and, as a consequence the companies do not pollute. However, if the marginal disutility of polluting is lower than the abatement cost, then the pollution tax is also lower than the abatement cost. It is for this reason that the companies would rather pay the pollution tax than assume the cost of abating the pollution. Thus, the companies do not reduce the pollution they generate, even by a minimal amount.

5. CONCLUSIONS

One of the fundamental objectives of the countries is to ensure that the companies are competitive in international and national markets, in order to achieve permanent economic development. Unfortunately, sustainable development is not always implicit in economic progress. In this sense, strategic environmental policy tends to guarantee that economic growth occurs in harmony with a healthy environment, controlling the quantity of pollutants emitted by companies while guaranteeing, to a degree, their productivity.

Generally, the application of instruments of environmental control tends to lead to an increase the companies' production costs, which is accompanied by a drop in their productivity. Governments should thus be very careful not to impose too strict environmental regulation measures that threaten competitiveness, industrial activity and the survival of national companies. Therefore, environmental control measures can be considered as barriers to trade, with their implications widely debated in both international trade and environmental forums.

The present study develops a partial equilibrium model, under reciprocal dumping conditions for bilateral trade in a homogeneous good between two different-sized countries, in which two heterogeneous companies located in each country compete under Cournot competition conditions. In order to control the emission of pollutants, the governments of both countries use pollution taxes, which consist in levying an amount against the companies per unit of pollution emitted. While this does mean that those companies that pollute more pay more, the companies have the adequate technology for reducing the emissions caused by their production processes.

This study determines the optimal pollution tax that maximizes the wellbeing of the two countries involved in the reciprocal dumping, in both a cooperative and non-cooperative environment. This enables strategic environmental policy to be deduced relative to both the optimal values for the pollution tax and the cost structure for the companies, considered, principally, to consist of the abatement cost and the marginal disutility of polluting. However, the application of said optimal environmental policy directly affects the social welfare function of the two countries, in which the following are harmoniously included: the benefit to the companies; consumer surplus; the government's revenue from the collection of the pollution tax; and, the social cost of polluting.

Under the non-cooperative framework, the optimal pollution tax depends, in the first place, on the asymmetry between the countries, the efficiency of their production processes, the companies' production quotas (for product for both local consumption and export), and the marginal disutility of polluting.

If the marginal disutility of polluting is sufficiently high, the government applies a positive tax; both in the case of, a small country and a large country; as in the case of countries with a similar size. In this case, the adverse effect that pollution causes to human health is taken more into account than the other components of the countries' wellbeing. In the case of similar-sized countries, if the export market size of the foreign country is significantly larger than the export market in the domestic country, the government favors the productivity of the local companies by not levying the pollution tax, although this causes damage to the environment.

On the other hand, under the cooperative framework, both countries agree to set a cooperative pollution tax, taking into account the effect of the optimal tax on the wellbeing of the other country. In other words, both governments will decide on the optimal pollution tax, which affects not only the local damage caused by pollution on the health of the population, but also the consumer and producer surpluses in the other country. Thus, in the cooperative environment, the optimal pollution tax depends also on the asymmetry between the countries, the efficiency of the production process, the quantities of the good produced (for either local consumption or export), and the marginal disutility of polluting.

When the marginal disutility of polluting is significantly high (independent of the relative size of the countries), reducing pollution is of maximum priority for the governments, as people's health and the preservation of the environment is valued higher than the benefit to the companies and the consumer surplus. Finally, for similar-sized countries, the governments will always apply a tax that is either lower or higher depending on both the marginal disutility of polluting and the companies' production quotas. Namely, they will regulate emissions by either increasing or decreasing the pollution tax in accordance with changes to the marginal disutility and the quantities produced by the companies. They will thus maintain a harmonious balance between the environmental damage caused by pollution on the one hand, and the companies' utility and the benefit for consumers on the other.

Finally, if the cost of the marginal disutility of polluting exceeds the abatement cost, then the optimal tax is higher than the abatement cost. In this case, the companies opt to assume the cost of reducing emissions and, thus, they decrease their emissions completely. However, if the marginal disutility of polluting is lower than the abatement cost, then the optimal tax is lower than the abatement cost. In this case, the companies opt to pay the pollution tax and refrain from reducing their emissions in any way.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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