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Transboundary Pollution, R&D Spillovers and International Trade

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Transboundary Pollution, R&D Spillovers and International Trade

Summary

We consider a non-cooperative symmetric three-stage game played by a pair of regulator-firm hierarchies to capture the scale and technological effects of opening markets to international trade. Each firm produces one good sold on the market. The production process generates pollution characterized by a fixed emission/output ratio, and crosses the borders. Firms can invest in R&D in order to lower their emission ratio, and this activity is characterized by positive R&D spillovers (β).

We show that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transboundary pollution.

When the R&D spillover increases, pollution decreases in most cases, and increases in some others. However, the social welfare improves with β .

Opening markets to international trade leads to both more investment in R&D and more production, and to a lower emission ratio. In most cases, pollution in common market is lower than in autarky, implying a greater social welfare. Nevertheless, in some other cases, international trade increases pollution and therefore reduces the social welfare.

Keywords: Transboundary pollution, R&D spillovers, Common market, Social welfare

JEL: D62, F12, O32

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1. Introduction

We develop a dynamic theoretical model to show how R&D spillovers and the competition of firms on the common market help non-cooperating countries to internalize transboundary pollution. This model also captures the scale and technological effects of opening markets to international trade, and shows that, in most cases, free mobility of goods among countries reduces pollution and improves the social welfare. Thus, this work is related to the literature on transboundary pollution and to the one on free trade and the environment. To our knowledge, there is no published theoretical work that studies transboundary pollution in the context of R&D possibilities and/or studies the technological effect of free trade in presence of transfrontier pollution, while taking into account the impact on the social welfare.

Examples of damages engendered by transfrontier pollution are the ozone layer depletion and global warming which are caused by the total emissions of gases such as the carbon dioxide. Transboundary pollution is therefore a negative externality among countries which usually does not lead non-cooperating countries to the Pareto-optimality. However, some authors have shown that non-cooperating governments can reach the first best under some conditions (Hoel (1997), Zagonari (1998)). Other studies have been interested in the effect of asymmetric information on transboundary externalities (Bac (1996), Petrakis and Xepapadeas (1996), Mansouri and Ben Youssef (2000)).

The relation between international trade and pollution can be explained by three main effects. The scale effect linking pollution to the scale of production and it is expected that free trade increases production and therefore pollution. The composition effect admits that certain dirty industries could relocate in countries with more lenient regulations. The technological effect refers to the possibility that international competition may encourage the innovation and diffusion of cleaner technologies to reduce the pollution intensity.

Copeland and Taylor (1995) show that free trade may raise world pollution, and because pollution crosses the borders, uncoordinated regulation of pollution at the national level does not eliminate all market failures, and consequently free trade

does not necessarily raise welfare. Fernandez (2002) examines empirically the effects of trade liberalization on transboundary water pollution between the United States and Mexico. She shows that trade liberalization gives incentives to use wastewater as input to produce the traded cotton, thus reducing pollution. P echoux and Pouyet (2003) show that, under incomplete information, international competition generated by the common market enables regulators to reduce the informational rents captured by firms, thereby reinforcing the need to open the markets to international competition. Many papers (Copeland and Taylor (1994), Reppelin-Hill (1999), Antweiler et al. (2001)) highlight the technological effect but they don't consider transboundary pollution and don't prove any result concerning the welfare effects of free trade.

This paper differs from the existing literature by studying a three-stage game in which R&D is carried out to reduce the emissions per-unit of production, in the context of R&D spillovers and transboundary pollution. This model also captures the scale and technological effects and tries to answer the question of whether opening markets to international trade reduces pollution and increases the social welfare.

We consider a non-cooperative and symmetric three-stage game played by two regulator-firm hierarchies. In the third stage, each firm produces one good sold on the market. The production process generates pollution characterized by a fixed emission/output ratio, and crosses the borders. In the second stage, firms can invest in R&D in order to lower their emission ratio. As in D'Aspremont and Jacquemin (1988) where firms invest in R&D to lower their per-unit production cost, this innovation activity is characterized by positive R&D spillovers (β). In the first stage, regulators propose non-cooperatively their contracts which should be accepted by their respective firms while giving the non-cooperative socially optimal levels of pollution (or production) and R&D. We study the complete information context. Our objective is to assess the role of R&D spillovers and the opening of markets in the control of transboundary pollution, and to compare the equilibrium values in autarky and common market. We hope to contribute to the understanding of the

interaction between the scale and technological effects in case of transboundary pollution.

We show that without R&D spillover ($\beta=0$), transboundary pollution is not internalized in the autarky regime. The higher R&D spillovers are, the higher is the proportion of transboundary pollution internalized by non-cooperating countries. Consequently, in most cases, pollution decreases with the R&D spillover whereas the social welfare increases. Surprisingly, in some other cases, pollution increases with β . Moreover, opening markets to international trade helps countries to better internalize transboundary pollution through firms' competition on the common market.

International competition leads to both more investment in R&D and more production, and to a lower emission ratio. When the sensitivity of consumers to the environment is sufficiently low, pollution in common market is lower than in autarky, implying a greater social welfare. Nevertheless, when the sensitivity of consumers to the environment and the investment cost parameter are high enough, pollution in common market is higher than in autarky; thus, the non-internalized transboundary pollution may be greater, even if opening markets enables to better internalize the transfrontier externality; moreover, the increase of production and innovation may decrease the profit of firms, leading to a diminution of the social welfare.

The paper is organized as follows. Section 2 presents the basic model in autarky, resolves it and exhibits the role of the R&D spillovers for the internalization of transboundary pollution. Section 3 deals with the case where markets are opened to international trade and shows how this contributes to internalize transborder pollution. Section 4 compares the equilibrium in autarky and common market, and section 5 gives some comparative static about the R&D spillover parameter. Finally, section 6 concludes. All the proofs of the propositions are gathered in the appendix.

2. Autarky

We consider a symmetric model consisting of two countries and two firms. Firm i located in country i is a regional monopoly and produces good i in quantity q_i sold in the domestic market with the following inverse demand function: $p_i = a - 2q_i, a > 0$. The market size of each country is therefore $a/2$.

The production process generates pollution and firms can invest in R&D in order to lower their fixed emission/output ratio. The level x_i of R&D costs $kx_i^2, k > 0$.

If we denote the marginal cost of production by $\theta > 0$, the profit of firm i is : $\Pi_i^a = p_i(q_i)q_i - \theta q_i - kx_i^2$.

The innovation activity carried out by the firms is characterized by positive externalities which imply that a proportion β of each firm's R&D level gratuitously spills over to the other firm. Therefore, the direct external effect of firm j 's R&D level is to lower firm i 's emission/output ratio. This can be made possible by scientific communications, scientific exchanges or intelligence activities, which we assume have negligible costs. By normalizing the emissions per-unit of production to one without innovation, the emission/output ratio of firm i is :

$$e_i = 1 - x_i - \mathbf{b}x_j, 0 \leq \mathbf{b} < 1, 0 < x_i + \mathbf{b}x_j < 1$$

The emission of pollution of firm i is therefore : $E_i = e_i q_i$.

There are also negative externalities between countries through transborder pollution. Damages caused to country i are: $D_i = \mathbf{a}E_i + \mathbf{g}E_j, \mathbf{a} > 0, \mathbf{g} > 0$.

Notice that even when α and γ are different, the model still remains symmetric because these parameters are the same for the two countries. This damage function can explain a pure transfrontier pollution problem when $\alpha = d(1-t)$ and $\gamma = dt$, where $0 < t < 1$ is the proportion of pollution of firm j exported to country i . It can also explain an international environmental problem, when $\alpha = \gamma$, because damages in one country become a function of the total pollution. To explain how transfrontier pollution can be internalized, we will separate the negative effect of the foreign pollution from the one of the home pollution by working with α and γ separately up to section 3, and then, to facilitate our computations, we will assimilate γ to α .

The consumer surplus in country i engendered by the consumption of q_i is $CS_i^a = \int_0^{q_i} p_i(t)dt - p_i(q_i)q_i = q_i^2$.

Since firm i is a regional monopoly that pollutes the environment, it should be regulated. The regulator can use two types of instruments : an emission tax per-unit of pollution to induce the non-cooperative socially optimal levels of production and pollution, and a subsidy per-unit of R&D to induce the non-cooperative socially optimal levels of R&D and emission/output ratio. Unfortunately, computations are not easy to do with this method of regulation. Indeed, the regulator must choose both the non-cooperative socially optimal emission tax and subsidy in the first stage given the reaction of the firm which will choose its non-cooperative optimal levels of R&D and production in the second and third stages, respectively. So, we consider another method of regulation which eases computations.

In the first stage, each regulator offers to his firm a contract (q_i, x_i, T_i) where q_i and x_i are the levels of production and innovation to be attained by firm i , and T_i is a monetary transfer inducing the firm to accept this contract. The value of T_i is as such that the net profit of the firm will be at least equal to its reservation utility level. Let's notice that this monetary transfer will not appear in the social welfare function because it is a pure transfer from the regulator to the firm i.e. we suppose that there is no marginal social cost of public funds.¹ In the second stage, firms invest in R&D, and in the third one, they produce the contracted quantities.

The social welfare of a country is equal to the consumer surplus minus damages plus the profit of the firm :

$$S_i^a(q_i, q_j, x_i, x_j, \mathbf{b}) = CS_i^a(q_i) - D_i(q_i, q_j, x_i, x_j, \mathbf{b}) + \Pi_i^a(q_i, x_i) \quad (1)$$

or written otherwise :

$$S_i^a = q_i^2 - \mathbf{a}(1 - x_i - \mathbf{b}x_j)q_i - \mathbf{g}(1 - x_j - \mathbf{b}x_i)q_j + (a - 2q_i)q_i - \mathbf{q}q_i - kx_i^2 \quad (2)$$

¹ The resolution of the autarky and common market cases is possible if we suppose the existence of positive marginal social cost of public funds. Unfortunately, the comparison of the equilibrium values in the two market regimes becomes very difficult to do.

Expression (2) shows that in the third stage when regulator i chooses his production quantity q_i , the pollution coming from country j is not internalized. This is general for static models characterized by a linear damage function with respect to the total pollution, or a separable one with respect to the pollution remaining at home and the one received from the other country.² However, in the second stage when regulator i chooses his level of R&D x_i , transboundary pollution is partially internalized if there is R&D spillovers ($\beta \neq 0$). The higher the positive externality is, the greater proportion of the negative externality is internalized.

$$\text{The first order condition of the third stage is : } \frac{\partial S_i^a}{\partial q_i} = 0 \quad (3)$$

The resolution of (3) gives :

$$q_i^a = \frac{1}{2} [a - q - \alpha(1 - x_i - \beta x_j)] \quad (4)$$

From (4), we have :

$$\frac{\partial q_i^a}{\partial x_i} = \frac{\alpha}{2} \quad \text{and} \quad \frac{\partial q_i^a}{\partial x_j} = \frac{\alpha\beta}{2} \quad (5)$$

Therefore, the quantity produced by a firm increases with its own R&D level, and with the R&D level of the other firm in case of positive spillovers, because they reduce its emission/output ratio.

Using equality (3), the first order condition of the second stage is reduced to :

$$\frac{dS_i^a}{dx_i} = \frac{\partial q_j}{\partial x_i} \frac{\partial S_i^a}{\partial q_j} + \frac{\partial S_i^a}{\partial x_i} = 0 \quad (6)$$

The symmetric³ solution of (6), using (4) and (5), is :

$$x_i^a = \frac{(\alpha + \beta\alpha)(a - q) - \alpha(\alpha + 2\beta\alpha)}{4k - (1 + \beta)\alpha(\alpha + 2\beta\alpha)} \quad (7)$$

Expression (7) confirms the fact that without R&D spillovers, transboundary pollution is completely non internalized. The higher β is, the greater proportion of transboundary pollution is internalized. Part of this negative externality is

² If the damages are not linear nor separable, the transboundary pollution is partially non-internalized.

³ We look for the symmetric equilibrium because, first, the model is symmetric and, second, computations are easier.

internalized when a country chooses its level of R&D, because such a choice will affect the emission ratio of the firm of the other country in case of R&D spillovers, which will, in turn, affect the pollution received.

This strategic interaction with transboundary pollution recalls the analysis of Santore et al. (2001), even though their model is drastically different from the one of this paper. They examine the strategic behavior of state-level utility regulators when pollution spillovers among countries are asymmetric and show that strategic behavior is possible because a regulator's environmental policy indirectly affects the price of permits and, therefore, abatement in other states.

To assure that the quantity given by (7) is positive, we need that :

$$a - \mathbf{q} > \frac{\mathbf{a}(\mathbf{a} + 2\mathbf{bg})}{\mathbf{a} + \mathbf{bg}} \quad (\text{C.1}) \quad , \quad \text{and} \quad k > \frac{1}{4}(1 + \mathbf{b})\mathbf{a}(\mathbf{a} + 2\mathbf{bg}) \quad (\text{C.2})$$

This last inequality guarantees the second order condition of equation (6).

$$\text{We also need that } (1 + \mathbf{b})x_i^a < 1 \Leftrightarrow k > \frac{1}{4}(1 + \mathbf{b})(\mathbf{a} + \mathbf{bg})(a - \mathbf{q}) \quad (\text{C.3})$$

The symmetric production quantities are given by (4) :

$$q_i^a = \frac{1}{2}[(1 + \mathbf{b})\mathbf{a}x_i^a + (a - \mathbf{q}) - \mathbf{a}] \quad (8)$$

Condition (C.1) guarantees that the above quantities are positive.

3. Common market

When markets are opened to international trade, the inverse demand function of the perfect substitute goods produced by firms becomes : $p = a - (q_i + q_j)$. The size of the integrated market is a.

The firms profits are : $\Pi_i^{cm} = p(q_i, q_j)q_i - \mathbf{q}q_i - kx_i^2$.

The total consumer surplus is equally divided between the two symmetric countries : $CS_i^{cm} = \frac{1}{2} \left[\int_0^{q_i+q_j} p(t)dt - p(q_i + q_j)(q_i + q_j) \right] = \frac{1}{4}(q_i + q_j)^2$.

The social welfare of country i is :

$$S_i^{cm}(q_i, q_j, x_i, x_j, \mathbf{b}) = CS_i^{cm}(q_i, q_j) - D_i(q_i, q_j, x_i, x_j, \mathbf{b}) + \Pi_i^{cm}(q_i, q_j, x_i) \quad (9)$$

The first order condition of the third stage is : $\frac{\mathcal{J}S_i^{cm}}{\mathcal{J}q_i} = 0$ (10)

The resolution of (10) is :

$$q_i^{cm} = \frac{1}{2} \left[\frac{1}{2} (3 - \mathbf{b}) \mathbf{a} x_i + \frac{1}{2} (3\mathbf{b} - 1) \mathbf{a} x_j + (a - \mathbf{q}) - \mathbf{a} \right] \quad (11)$$

From (11), we have :

$$\frac{\mathcal{J}q_i^{cm}}{\mathcal{J}x_i} = \frac{1}{4} (3 - \mathbf{b}) \mathbf{a} \quad \text{and} \quad \frac{\mathcal{J}q_i^{cm}}{\mathcal{J}x_j} = \frac{1}{4} (3\mathbf{b} - 1) \mathbf{a} \quad (12)$$

When a firm increases its level of R&D, this has two opposite effects on its production. The first is positive and enables it to produce more because its emission/output ratio is lowered. The second is negative, because through R&D spillovers the rival firm has a lower emission ratio enabling it to produce more on the common market, which forces the initial firm to reduce its production. The combination of these two effects always increases production ($\mathcal{J}q_i^{cm} / \mathcal{J}x_i > 0$); however, such an increase is less important with higher R&D externalities ($\mathcal{J}^2 q_i^{cm} / \mathcal{J}x_i \mathcal{J}\mathbf{b} < 0$).

When the rival firm increases its level of innovation, it affects the production of the firm both positively and negatively. Indeed, through β , the firm has a lower emission/output ratio which enables it to produce more. But since the rival firm has a lower pollution ratio it can produce more, forcing the firm to reduce its production. The first positive effect dominates when β is high enough ($\mathcal{J}q_i^{cm} / \mathcal{J}x_j > 0 \Leftrightarrow \mathbf{b} > 1/3$).

By using (10), the first order condition of the second stage is reduced to :

$$\frac{dS_i^{cm}}{dx_i} = \frac{\mathcal{J}q_j}{\mathcal{J}x_i} \frac{\mathcal{J}S_i^{cm}}{\mathcal{J}q_j} + \frac{\mathcal{J}S_i^{cm}}{\mathcal{J}x_i} = 0 \quad (13)$$

Using (11) and (12), the symmetric solution of (13) is :

$$x_i^{cm} = \frac{2(\mathbf{a} + \mathbf{b}\mathbf{g})(a - \mathbf{q}) - \mathbf{a}[2\mathbf{a} + (5\mathbf{b} - 1)\mathbf{g}]}{8k - (1 + \mathbf{b})\mathbf{a}[2\mathbf{a} + (5\mathbf{b} - 1)\mathbf{g}]} \quad (14)$$

In common market, transboundary pollution is internalized through two channels : R&D spillovers and competition of firms on the common market. Indeed, when country i chooses its level of innovation this affects the emission ratio of its firm and

therefore its production and the production of the competing firm, which in turn affects the pollution received by country i . Therefore, opening the markets to international competition helps non-cooperating countries to better internalize transboundary pollution, when R&D possibilities are considered.

The second order condition of the second stage is verified iff :

$$k > \frac{1}{4}(3\mathbf{b}-1)\mathbf{b}\mathbf{a}\mathbf{g} + \frac{1}{16}(3\mathbf{b}^2 - 6\mathbf{b} + 7)\mathbf{a}^2 \quad (\text{C.4})$$

The solution given by (14) is positive when :

$$a - \mathbf{q} > \frac{\mathbf{a}[2\mathbf{a} + (5\mathbf{b} - 1)\mathbf{g}]}{2(\mathbf{a} + \mathbf{b}\mathbf{g})} \quad (\text{C.5}) \quad , \quad \text{and} \quad k > \frac{1}{8}(1 + \mathbf{b})\mathbf{a}[2\mathbf{a} + (5\mathbf{b} - 1)\mathbf{g}] \quad (\text{C.6})$$

$$\text{We also need that } (1 + \mathbf{b})x_i^{cm} < 1 \Leftrightarrow k > \frac{1}{4}(1 + \mathbf{b})(\mathbf{a} + \mathbf{b}\mathbf{g})(a - \mathbf{q}) \quad (\text{C.7})$$

The symmetric production quantities are given by (11) :

$$q_i^{cm} = \frac{1}{2}[(1 + \mathbf{b})\mathbf{a}x_i^{cm} + (a - \mathbf{q}) - \mathbf{a}] \quad (\text{15})$$

A sufficient condition for the above production quantities to be positive is :

$$(a - \theta) > \alpha \quad (\text{C.8})$$

Notice that in both market regimes, countries can implement the non-cooperative socially optimal allocations by using two instruments: a subsidy per-unit of R&D to induce the desired level of innovation, and a tax per-unit of pollution to induce the desired levels of pollution and production.

In the remaining of the paper, to simplify our computations, we will replace γ by α .

In the following propositions, we suppose that conditions (C.1) to (C.3) and (C.4) to (C.8) are verified for the autarky and common market regimes, respectively. Notice that these conditions, when $\gamma = \alpha$, imply that α is sufficiently low and k is sufficiently high. Indeed, when the sensitivity of consumers to the environment is high, the investment in R&D may be too high when it does not costs much, leading to a negative emission ratio which has no economic meaning.

4. Common market versus autarky

In the previous sections we have showed that opening markets to international trade better internalizes transborder pollution. This suggests that the levels of R&D and production are higher in common market. But what about emissions and social welfare ?

Proposition 1. *The R&D level and production are higher in common market than in autarky, whereas the emission/output ratio is lower.*

Opening markets to international trade better internalizes transboundary pollution, which leads to a higher R&D level than in autarky. Consequently, the emission ratio is lower, enabling firms to produce more in common market.⁴

It's interesting to emphasize that these differences are due to the second stage of R&D because if the innovation levels were equal in autarky and common market, then from (8) and (15), productions, and thus and all the equilibrium values, would be equal.

Proposition 2. *International trade reduces pollution when α is sufficiently low, and increases it when α and k are high enough.*

When we increase the R&D level, the emission per-unit of production decreases and production increases, which, in most cases, lowers pollution implying that pollution in common market is lower than in autarky. However, when α is sufficiently high, the R&D level provided to internalize pollution is important and the emission ratio is low; when markets are opened to international trade, the

⁴ Let's notice that if there was no negative externality between countries, then the equilibrium values in autarky and common market would be identical. Indeed, if $\gamma=0$, expressions (7) and (14) show that the R&D levels are equal which implies that all the other equilibrium values are equal in the two market regimes.

emission/output ratio slightly decreases when k is high enough because the marginal cost of R&D is increasing, whereas production significantly increases, leading to an increase of pollution. Thus, the better internalization of transborder pollution engendered by the competition of firms on the common market is materialized by an increase in the R&D level which is a choice variable, and does not necessarily imply a decrease of pollution. This implies that the non-internalized transborder pollution may be greater in common market even if opening markets enables to capture a greater proportion of the transfrontier externality.

Proposition 3. *International trade increases the social welfare when α is sufficiently low, and decreases it when α and k are high enough.*

The results of proposition 3 are in concordance with those of propositions 1 and 2. Indeed, in most cases, opening markets to international competition increases production and innovation and decreases pollution, leading to an increase in social welfare. Nevertheless, when α and k are sufficiently high, pollution in common market is higher than in autarky ; moreover, international trade increases production and innovation which may reduce the profit of firms; the combination of these effects leads to a lower social welfare in common market. Since this last situation happens under very restrictive conditions⁵, we can say that, in general, opening markets to international trade reduces pollution and improves the social welfare.

5. The effect of R&D spillovers

So far, we have shown that a higher β helps non-cooperating countries to internalize a greater proportion of transborder pollution. It is therefore expected that when the R&D spillover increases, pollution and the emission/output ratio decrease

⁵ We recall that the equilibrium conditions imply that α is sufficiently low. So, when, in addition, α is high enough, the set to which belongs α is very restricted.

whereas the social welfare increases. The following proposition will confirm these predictions in almost all the cases, and shows when we have unexpected results.

Proposition 4. *i) When α is sufficiently low, both the equilibrium levels of R&D and production increase with β , whereas the emission/output ratio decreases with β . However, when α and k are sufficiently high, we have the opposite results.*

ii) In most cases pollution decreases with β , and it increases only when α is neither too high nor too low and k is sufficiently high.

iii) The social welfare increases with the R&D spillover.

We know that when β increases, a greater proportion of transboundary pollution is internalized by non-cooperating regulators, which in most cases leads to a diminution of pollution. Such a diminution of pollution can be realized by two manners.

The first happens when α is sufficiently low, and uses the fact that the emission ratio decreases with β whereas production increases. The second happens when α and k are high enough. Indeed, when α is sufficiently high, the R&D level provided is very high, so that to internalize a greater proportion of transboundary pollution while reducing pollution, it is preferable to increase the emission ratio (by reducing the R&D level) and to reduce production, in the case of a sufficiently high investment cost parameter k .

In some cases, pollution increases with the R&D spillover. Indeed, when α is neither too high nor too low and k is sufficiently high, production increases with β whereas the emission ratio decreases but not in a sufficiently amount because the innovation level and the investment cost parameter are very high, leading to an increase of pollution.

Since the R&D spillover is a free positive externality, the social welfare improves when it is increased. In the Appendix, we demonstrate this for almost all the cases concerning α and k , and we think there is no reason to get the opposite result for the remaining cases not considered.

6. Conclusion

This model captures the scale and technological effects and tries to answer the question of whether opening markets to international trade, in case of transboundary pollution, reduces pollution and increases social welfare. It also studies the role of the positive R&D spillover and the competition of firms on the common market in the internalization of the transfrontier negative externality.

We consider a non-cooperative and symmetric three-stage game played by two regulator-firm hierarchies. Each firm produces one good sold on the market and can invest in R&D in order to lower its emissions per-unit of production. This research activity is characterized by positive R&D spillovers.

In autarky, we show that without R&D spillovers ($\beta=0$), transboundary pollution is completely non-internalized. The higher R&D spillover is, the higher the proportion of transboundary pollution internalized is. Moreover, opening markets to international trade helps competing countries to better internalize transborder pollution through the competition of firms on the common market.

Consequently, when the R&D spillover increases, pollution decreases in most cases whereas the social welfare improves. Therefore, it is recommended for countries to voluntarily increase their positive R&D externality through scientific communications or exchanges. The issue of cooperation in R&D has not been examined in this paper, but we think that it would be beneficial for countries. In addition, if countries fully cooperate, then transboundary pollution is completely internalized and they reach the first best.

Opening markets to international trade leads to both more investment in R&D and more production. When α is sufficiently low, pollution in common market is lower than in autarky implying a greater social welfare. Nevertheless, when a and k are high enough, international trade increases pollution and therefore reduces the social welfare. Indeed, the non-internalized transborder pollution may be greater, even if opening markets enables to better internalize the transfrontier externality; moreover, the increase of production and innovation may decrease the profit of firms. Since this last situation happens under very restrictive conditions, we can say that, in general,

opening markets to international trade reduces pollution and improves the social welfare.

Even if we came to our results by a simple but intuitive model, many of them could be generalized to a more complicated context. In this paper, we have assigned the same importance to consumer welfare and profit of the firm. A possible extension of this work is to give these latter different weights i.e. to suppose that there is positive cost of raising public funds. Another extension is to introduce asymmetric information between the regulators and their respective firms concerning their production costs or R&D activity. This may reinforce the potential gain to open markets to international trade because the competition on the common market may decrease the informational rents captured by firms.

Appendix

When we replace γ by α , conditions (C.1) to (C.8) become :

$$a - \mathbf{q} > \frac{(1 + 2\mathbf{b})\mathbf{a}}{1 + \mathbf{b}} \quad (\text{C.1}), \quad k > \frac{1}{4}(1 + \mathbf{b})(1 + 2\mathbf{b})\mathbf{a}^2 \quad (\text{C.2}), \quad k > \frac{1}{4}(1 + \mathbf{b})^2 \mathbf{a}(a - \mathbf{q}) \quad (\text{C.3})$$

$$k > \frac{1}{16}(15\mathbf{b}^2 - 10\mathbf{b} + 7)\mathbf{a}^2 \quad (\text{C.4}), \quad a - \mathbf{q} > \frac{(1 + 5\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})} \quad (\text{C.5}), \quad k > \frac{1}{8}(1 + \mathbf{b})(1 + 5\mathbf{b})\mathbf{a}^2 \quad (\text{C.6}),$$

$$(\text{C.7}) = (\text{C.3}), \quad a - \theta > \alpha \quad (\text{C.8}).$$

These conditions mean that α is sufficiently low and k is sufficiently high.

Using (7) and (14) for $\gamma = \alpha$, the symmetric equilibrium values of R&D become :

$$x_i^a = \frac{\mathbf{a}[(1 + \mathbf{b})(a - \mathbf{q}) - (1 + 2\mathbf{b})\mathbf{a}]}{4k - (1 + \mathbf{b})(1 + 2\mathbf{b})\mathbf{a}^2} \quad \text{and} \quad x_i^{cm} = \frac{\mathbf{a}[2(1 + \mathbf{b})(a - \mathbf{q}) - (1 + 5\mathbf{b})\mathbf{a}]}{8k - (1 + \mathbf{b})(1 + 5\mathbf{b})\mathbf{a}^2} \quad (16)$$

A) Proof of Proposition 1

From (16), we have :

$$x_i^{cm} - x_i^a = \frac{(1 - \mathbf{b})\mathbf{a}^2 [4k - (1 + \mathbf{b})^2 \mathbf{a}(a - \mathbf{q})]}{[8k - (1 + \mathbf{b})(1 + 5\mathbf{b})\mathbf{a}^2][4k - (1 + \mathbf{b})(1 + 2\mathbf{b})\mathbf{a}^2]}$$

From (C.2), (C.3) and (C.6), we get $x_i^{cm} - x_i^a > 0$, which implies that $e_i^{cm} < e_i^a$, and from (8) and (15), we also have $q_i^{cm} > q_i^a$.

B) Proof of Proposition 2

To compare the emission levels in autarky and common market, we rewrite the symmetric equilibrium pollution level of a firm as $E_i(x_i) = (1 - (1 + \mathbf{b})x_i)q_i(x_i)$, where

$q_i(x_i)$ are given by (8) and (15). Thus, $\frac{dE_i(x_i)}{dx_i} = \frac{1}{2}(1 + \mathbf{b})[-2(1 + \mathbf{b})\mathbf{a}x_i + 2\mathbf{a} - (a - \mathbf{q})]$.

$$\mathbf{i}) \frac{dE_i(x_i)}{dx_i} < 0 \Leftrightarrow x_i > x^1 = \frac{2\mathbf{a} - (a - \mathbf{q})}{2(1 + \mathbf{b})\mathbf{a}}$$

The above inequality is verified by any $x_i > 0$ when $(a - \theta) > 2\alpha$.

Therefore, if $(a - \theta) > 2\alpha$, then $dE_i(x_i) / dx_i < 0 \quad \forall x_i > 0$, and since $x_i^{cm} > x_i^a$, this implies that $E_i^{cm} < E_i^a$.

$$\mathbf{ii}) \frac{dE_i(x_i)}{dx_i} > 0 \Leftrightarrow x_i < x^1. \text{ Therefore, if } (a - \theta) < 2\alpha, \text{ we have } dE_i(x_i) / dx_i > 0 \quad \forall x_i < x^1.$$

To compare E_i^{cm} and E_i^a , we need that $x_i^{cm} < x^1$.

$$x_i^{cm} - x^1 = \frac{8k[(a - \mathbf{q}) - 2\mathbf{a}] + (1 + \mathbf{b})(3 - \mathbf{b})\mathbf{a}^2(a - \mathbf{q})}{2(1 + \mathbf{b})\mathbf{a}[8k - (1 + \mathbf{b})(1 + 5\mathbf{b})\mathbf{a}^2]} < 0 \Leftrightarrow k > k^1 = \frac{(1 + \mathbf{b})(3 - \mathbf{b})\mathbf{a}^2(a - \mathbf{q})}{8(2\mathbf{a} - (a - \mathbf{q}))}$$

Therefore, if $(a - \theta) < 2\alpha$ and $k > k^1$, then $dE_i(x_i) / dx_i > 0 \quad \forall x_i < x^1$, implying that $E_i^{cm} > E_i^a$.

C) Proof of Proposition 3

By using expressions (2) and (9) for the symmetric case, the symmetric equilibrium social welfare of a country can be written as :

$$S_i(x_i) = -(q_i(x_i))^2 - 2\mathbf{a}(1 - (1 + \mathbf{b})x_i)q_i(x_i) + (a - \mathbf{q})q_i(x_i) - kx_i^2$$

where q_i and x_i could be the equilibrium values in autarky or common market. By using expressions (8) and (15), we can show that :

$$\frac{dS_i(x_i)}{dx_i} = \left[\frac{3}{2}(1 + \mathbf{b})^2 \mathbf{a}^2 - 2k \right] x_i + (1 + \mathbf{b})\mathbf{a}(a - \mathbf{q}) - \frac{3}{2}(1 + \mathbf{b})\mathbf{a}^2 \quad (17)$$

• Suppose that $k < \frac{3}{4}(1 + \mathbf{b})^2 \mathbf{a}^2$

The above inequality is not in contradiction with (C.2), (C.3), (C.4), (C.6) and (C.7).

$$\frac{dS_i(x_i)}{dx_i} > 0 \Leftrightarrow x_i > x^2 = (1 + \mathbf{b})\mathbf{a} \frac{2(a - \mathbf{q}) - 3\mathbf{a}}{4k - 3(1 + \mathbf{b})^2 \mathbf{a}^2}$$

Therefore, if $(a - \mathbf{q}) > \frac{3}{2}\mathbf{a}$ and $k < \frac{3}{4}(1 + \mathbf{b})^2 \mathbf{a}^2$, then $dS_i(x_i) / dx_i > 0$ " $x_i > 0$ ", implying that $S_i^{cm} > S_i^a$.

• Suppose that $k > \frac{3}{4}(1 + \mathbf{b})^2 \mathbf{a}^2$, then $\frac{dS_i(x_i)}{dx_i} > 0 \Leftrightarrow x_i < x^2$

If $(a - \mathbf{q}) > \frac{3}{2}\mathbf{a}$, then $x^2 > 0$ and we need to have $x_i^{cm} < x^2$.

$$x_i^{cm} - x^2 = \mathbf{a} \frac{4k[-2(1 + \mathbf{b})(a - \mathbf{q}) + (5 + \mathbf{b})\mathbf{a}] - 4(1 + \mathbf{b})(1 - \mathbf{b}^2)\mathbf{a}^2(a - \mathbf{q})}{[8k - (1 + \mathbf{b})(1 + 5\mathbf{b})\mathbf{a}^2][4k - 3(1 + \mathbf{b})^2 \mathbf{a}^2]}$$

If $(a - \mathbf{q}) > \frac{5 + \mathbf{b}}{2(1 + \mathbf{b})}\mathbf{a}$, then $x_i^{cm} < x^2$.

Thus, if $(a - \mathbf{q}) > \frac{5 + \mathbf{b}}{2(1 + \mathbf{b})}\mathbf{a}$ and $k > \frac{3}{4}(1 + \mathbf{b})^2 \mathbf{a}^2$, then $dS_i(x_i) / dx_i > 0$ " $x_i < x^2$ ", implying that $S_i^{cm} > S_i^a$.

Since $\frac{5 + \mathbf{b}}{2(1 + \mathbf{b})}\mathbf{a} > \frac{3}{2}\mathbf{a}$, then if $(a - \mathbf{q}) > \frac{5 + \mathbf{b}}{2(1 + \mathbf{b})}\mathbf{a}$, we have $dS_i(x_i) / dx_i > 0$ on an open interval containing x_i^a and x_i^{cm} , implying that $S_i^{cm} > S_i^a$.

Lastly, $\frac{dS_i(x_i)}{dx_i} < 0 \Leftrightarrow x_i > x^2$: true for any $x_i > 0$ when $(a - \mathbf{q}) < \frac{3}{2}\mathbf{a}$.

Therefore, if $(a - \mathbf{q}) < \frac{3}{2}\mathbf{a}$ and $k > \frac{3}{4}(1 + \mathbf{b})^2 \mathbf{a}^2$, then $dS_i(x_i) / dx_i < 0$ " $x_i > 0$ ", implying that $S_i^{cm} < S_i^a$.

D) Proof of Proposition 4

i)* The numerator of $\frac{1}{\mathbf{a}} \frac{dx_i^a(\mathbf{b})}{d\mathbf{b}}$ is $4k[(a - \mathbf{q}) - 2\mathbf{a}] + \mathbf{a}^2[2(1 + \mathbf{b})^2(a - \mathbf{q}) - (1 + 2\mathbf{b})^2 \mathbf{a}]$,

whereas the denominator is positive. Because of condition (C.1), the term between the above second square brackets is positive. Thus :

• If $(a - \theta) > 2\alpha$, then $dx_i^a(\mathbf{b}) / d\mathbf{b} > 0$.

• If $(a - \theta) < 2\alpha$, then $\frac{dx_i^a(\mathbf{b})}{d\mathbf{b}} < 0 \Leftrightarrow k > k^2 = \frac{\mathbf{a}^2[2(1 + \mathbf{b})^2(a - \mathbf{q}) - (1 + 2\mathbf{b})^2 \mathbf{a}]}{4[2\mathbf{a} - (a - \mathbf{q})]}$

The term $\frac{1}{\mathbf{a}} \frac{dx_i^{cm}(\mathbf{b})}{d\mathbf{b}}$ has the same sign than its numerator

$8k[2(a-\mathbf{q})-5\mathbf{a}]+\mathbf{a}^2[10(1+\mathbf{b})^2(a-\mathbf{q})-(1+5\mathbf{b})^2\mathbf{a}]$. Because of condition (C.5), the term between the second square brackets is positive. Thus :

• If $(a-\mathbf{q}) > \frac{5}{2}\mathbf{a}$, then $dx_i^{cm}(\mathbf{b})/d\mathbf{b} > 0$.

• If $(a-\mathbf{q}) < \frac{5}{2}\mathbf{a}$, then $\frac{dx_i^{cm}(\mathbf{b})}{d\mathbf{b}} < 0 \Leftrightarrow k > k^3 = \frac{\mathbf{a}^2[10(1+\mathbf{b})^2(a-\mathbf{q})-(1+5\mathbf{b})^2\mathbf{a}]}{8[5\mathbf{a}-2(a-\mathbf{q})]}$

* We have $e_i(\mathbf{b}) = [1 - (1+\mathbf{b})x_i(\mathbf{b})]$ and $\frac{de_i(\mathbf{b})}{d\mathbf{b}} = -x_i(\mathbf{b}) - (1+\mathbf{b})\frac{dx_i(\mathbf{b})}{d\mathbf{b}}$ (18)

The term $-\frac{1}{\mathbf{a}} \frac{de_i^a(\mathbf{b})}{d\mathbf{b}}$ has the same sign than its numerator

$4k[2(1+\mathbf{b})(a-\mathbf{q})-(3+4\mathbf{b})\mathbf{a}]+(1+\mathbf{b})^2\mathbf{a}^2(a-\mathbf{q})$. Therefore :

• If $(a-\mathbf{q}) > \frac{(3+4\mathbf{b})\mathbf{a}}{2(1+\mathbf{b})}$, then $de_i^a(\mathbf{b})/d\mathbf{b} < 0$.

• If $(a-\mathbf{q}) < \frac{(3+4\mathbf{b})\mathbf{a}}{2(1+\mathbf{b})}$ and k is high enough, then $de_i^a(\mathbf{b})/d\mathbf{b} > 0$.

The term $-\frac{1}{\mathbf{a}} \frac{de_i^{cm}(\mathbf{b})}{d\mathbf{b}}$ has the same sign than its numerator

$8k[4(1+\mathbf{b})(a-\mathbf{q})-2(3+5\mathbf{b})\mathbf{a}]+8(1+\mathbf{b})^2\mathbf{a}^2(a-\mathbf{q})$. Therefore :

• If $(a-\mathbf{q}) > \frac{(3+5\mathbf{b})\mathbf{a}}{2(1+\mathbf{b})}$, then $de_i^{cm}(\mathbf{b})/d\mathbf{b} < 0$.

• If $(a-\mathbf{q}) < \frac{(3+5\mathbf{b})\mathbf{a}}{2(1+\mathbf{b})}$ and k is high enough, then $de_i^{cm}(\mathbf{b})/d\mathbf{b} > 0$.

* From expressions (8), (15) and (18) we deduce $q_i(\mathbf{b}) = q_i(\mathbf{b}, x_i(\mathbf{b})) \Rightarrow$

$$\frac{dq_i(\mathbf{b})}{d\mathbf{b}} = \frac{\mathcal{J}q_i}{\mathcal{J}\mathbf{b}} + \frac{dx_i(\mathbf{b})}{d\mathbf{b}} \frac{\mathcal{J}q_i}{\mathcal{J}x_i} = -\frac{\mathbf{a}}{2} \frac{de_i(\mathbf{b})}{d\mathbf{b}} \quad (19)$$

Thus, the quantity produced and the emission ratio vary in opposite directions with respect to the R&D spillover.

ii) We have $E_i(\mathbf{b}) = e_i(\mathbf{b})q_i(\mathbf{b})$ and $\frac{dE_i(\mathbf{b})}{d\mathbf{b}} = \frac{de_i(\mathbf{b})}{d\mathbf{b}}q_i(\mathbf{b}) + e_i(\mathbf{b})\frac{dq_i(\mathbf{b})}{d\mathbf{b}}$

Using (19), (8) and (15), we establish that :

$$\frac{dE_i(\mathbf{b})}{d\mathbf{b}} = \frac{1}{\mathbf{a}} \frac{dq_i(\mathbf{b})}{d\mathbf{b}} [2\mathbf{a} - (a - \mathbf{q}) - 2(1 + \mathbf{b})\mathbf{a}x_i(\mathbf{b})] = \frac{1}{\mathbf{a}} \frac{dq_i(\mathbf{b})}{d\mathbf{b}} f_i(\mathbf{b}) \quad (20)$$

• If $(a - \theta) > 2\alpha$, then $dq_i(\mathbf{b}) / d\mathbf{b} > 0$ implying that $dE_i(\mathbf{b}) / d\mathbf{b} < 0$.

• Using the expression of $x_i^a(\mathbf{b})$, $f_i^a(\mathbf{b})$ has the sign of its numerator $4k[2\mathbf{a} - (a - \mathbf{q})] - (1 + \mathbf{b})\mathbf{a}^2(a - \mathbf{q})$. Therefore :

If $(a - \mathbf{q}) < \frac{(3 + 4\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})}$ and k is high enough, then $dq_i^a(\mathbf{b}) / d\mathbf{b} < 0$ implying that

$$dE_i^a(\mathbf{b}) / d\mathbf{b} < 0.$$

If $\frac{(3 + 4\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})} < a - \mathbf{q} < 2\mathbf{a}$ and k is high enough, then $dq_i^a(\mathbf{b}) / d\mathbf{b} > 0$ implying that

$$dE_i^a(\mathbf{b}) / d\mathbf{b} > 0.$$

• Using the expression of $x_i^{cm}(\mathbf{b})$, $f_i^{cm}(\mathbf{b})$ has the sign of its numerator $8k[2\mathbf{a} - (a - \mathbf{q})] - (3 - \mathbf{b})(1 + \mathbf{b})\mathbf{a}^2(a - \mathbf{q})$. Therefore :

If $(a - \mathbf{q}) < \frac{(3 + 5\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})}$ and k is high enough, then $dq_i^{cm}(\mathbf{b}) / d\mathbf{b} < 0$ implying that

$$dE_i^{cm}(\mathbf{b}) / d\mathbf{b} < 0.$$

If $\frac{(3 + 5\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})} < a - \mathbf{q} < 2\mathbf{a}$ and k is high enough, then $dq_i^{cm}(\mathbf{b}) / d\mathbf{b} > 0$ implying that

$$dE_i^{cm}(\mathbf{b}) / d\mathbf{b} > 0.$$

iii) Using expressions (2) and (9), the symmetric equilibrium social welfare of a country can be written as :

$$S_i(\mathbf{b}) = -(q_i(\mathbf{b}))^2 - 2\mathbf{a}E_i(\mathbf{b}) + (a - \mathbf{q})q_i(\mathbf{b}) - k(x_i(\mathbf{b}))^2$$

Deriving with respect to β and then using expressions (8), (15) and (20), we get :

$$\frac{dS_i(\mathbf{b})}{d\mathbf{b}} = \frac{dq_i(\mathbf{b})}{d\mathbf{b}} g_i(\mathbf{b}) - 2kx_i(\mathbf{b}) \frac{dx_i(\mathbf{b})}{d\mathbf{b}} \quad (21)$$

where $g_i(\mathbf{b}) = 3(1 + \mathbf{b})\mathbf{a}x_i(\mathbf{b}) + 2(a - \mathbf{q}) - 3\mathbf{a}$.

The previous results on the variations of $q_i(\mathbf{b})$ and $x_i(\mathbf{b})$ with respect to β , show that :

• If $\frac{(3 + 4\mathbf{b})\mathbf{a}}{2(1 + \mathbf{b})} < a - \mathbf{q} < 2\mathbf{a}$ and k is high enough, then $dS_i^a(\mathbf{b}) / d\mathbf{b} > 0$.

•If $\frac{(3+5\mathbf{b})\mathbf{a}}{2(1+\mathbf{b})} < a - \mathbf{q} < \frac{5}{2}\mathbf{a}$ and k is high enough, then $dS_i^{cm}(\mathbf{b}) / d\mathbf{b} > 0$.

•Using the expression of $x_i^a(\mathbf{b})$, $g_i^a(\mathbf{b})$ has the sign of its numerator $4k[2(a-\mathbf{q})-3\mathbf{a}]+(1-\mathbf{b}^2)\mathbf{a}^2(a-\mathbf{q})$.

Thus, if $(a-\mathbf{q}) < \frac{3}{2}\mathbf{a}$ and k is high enough, then $dS_i^a(\mathbf{b}) / d\mathbf{b} > 0$.

•Using the expression of $x_i^{cm}(\mathbf{b})$, $g_i^{cm}(\mathbf{b})$ has the sign of its numerator $8k[2(a-\mathbf{q})-3\mathbf{a}]+4(1-\mathbf{b}^2)\mathbf{a}^2(a-\mathbf{q})$.

Thus, if $(a-\mathbf{q}) < \frac{3}{2}\mathbf{a}$ and k is high enough, then $dS_i^{cm}(\mathbf{b}) / d\mathbf{b} > 0$.

•Using expressions (18) and (19), (21) becomes :

$$\frac{dS_i(\mathbf{b})}{d\mathbf{b}} = \frac{\mathbf{a}}{2} \left[x_i(\mathbf{b}) + (1+\mathbf{b}) \frac{dx_i(\mathbf{b})}{d\mathbf{b}} \right] \left[3(1+\mathbf{b})\mathbf{a}x_i(\mathbf{b}) + 2(a-\mathbf{q}) - 3\mathbf{a} \right] - 2kx_i(\mathbf{b}) \frac{dx_i(\mathbf{b})}{d\mathbf{b}}$$

Using the equality (17), we get :

$$\frac{dS_i(\mathbf{b})}{d\mathbf{b}} = \frac{\mathbf{a}}{2} x_i(\mathbf{b}) \left[3(1+\mathbf{b})\mathbf{a}x_i(\mathbf{b}) + 2(a-\mathbf{q}) - 3\mathbf{a} \right] + \frac{dx_i(\mathbf{b})}{d\mathbf{b}} \frac{dS_i(x_i(\mathbf{b}))}{d(x_i(\mathbf{b}))}$$

The previous results on $\frac{dx_i(\mathbf{b})}{d\mathbf{b}}$ and $\frac{dS_i(x_i)}{dx_i}$, imply that if $(a-\mathbf{q}) > \frac{5}{2}\mathbf{a}$,

then $\frac{dS_i(\mathbf{b})}{d\mathbf{b}} > 0$.

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