R&D in Cleaner Technology and International Trade*

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Abstract: We consider a non-cooperative three-stage game played by two regulator-firm hierarchies. We suppose that raising public funds is socially costly and that market sizes are large enough. Contrary to what might be expected, we show that opening markets to international trade increases the per-unit emission-tax and decreases the per-unit R&D subsidy. It also increases the R&D level, production, and pollution when the marginal damage of pollution is sufficiently high, and, consequently, decreases the emission ratio and the social welfare. However, we think that these results might change if the market sizes are not too large or if we introduce asymmetric information.

Keywords: Costly public funds; Market size; Common market; Emission-tax; R&D subsidy.

JEL classification : D62; F12; C72 ; L51; Q28

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1. Introduction

The relation between free trade and pollution can be explained by the scale, composition, technique and technological effects.

Copeland and Taylor (1994) developed a static two-country general equilibrium model to isolate the scale, composition and technique effects of international trade on pollution. They showed that trade liberalization may raise world pollution. Antweiler et al. (2001) conducted empirical tests using data on sulfur dioxide concentrations and showed that free trade reduces pollution. Reppelin-Hill (1999) empirically demonstrated that a cleaner technology (the electric arc furnace) is diffused more quickly in countries having more open trade regimes. Karp et al. (2001) showed that autarky is likely to Pareto-dominate free trade in the long run when the environment is fragile, and the result is reversed when the environment is resilient. Walz and Wellisch (1997) highlighted that welfare-maximizing governments of exporting countries preferred free trade even if countries subsidize their local industries indirectly through ecological dumping. Bruneau (2005) showed that regulation with inefficient instruments, such as design standards or concentration standards, can lead to net losses under trade liberalization even when emissions are optimally adjusted for trade. Péchoux and Pouyet (2003) showed that international competition enables regulators to reduce the informational rents captured by firms when these latter hold private information.

Closely linked to this work, is the one of Ben Youssef (2009). In this last paper, we considered a non-cooperative and symmetric three-stage game played by two regulator-firm hierarchies. We showed that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transfrontier pollution. International competition increases the per-unit emission-tax and decreases the per-unit R&D subsidy, and leads to a higher investment in R&D and production, and to a lower emission ratio. Pollution in common market is lower than in autarky in most cases, implying a greater social welfare, and the contrary occurs in some other cases. The present work differs from the previous one by the fact that we suppose that there is no transboundary pollution and no R&D spillovers.

However, we suppose the existence of positive marginal social cost of public funds which means, as it will be proved later on, that a higher weight is given to the profit of the domestic firm in the social welfare function. Consequently, the most results of the present paper come essentially from strategic trade policy considerations, whereas in the previous paper they are due essentially to the transboundary pollution distortion. Moreover, the present paper is more fitted for the introduction of asymmetric information.

We consider a non-cooperative and symmetric three-stage game played by a pair of regulator-firm hierarchies in presence of positive marginal social cost of public funds. In the third stage, each firm produces one good sold on the market. In the second stage, firms can invest in R&D in order to lower their fixed emission/output ratio. In the first stage, regulators announce non-cooperatively their emission-tax per-unit of pollution, R&D subsidy per-unit of the level of innovation, and a lump sum tax on profit. We study the complete information case and we suppose that the market sizes are sufficiently large. Our objective is to compare the non-cooperative socially optimal values in autarky and common market.

When markets are opened to international competition, the regulator increases his per-unit emission-tax to avoid damages to his environment, and decreases the per-unit R&D subsidy to avoid that the profit of the domestic firm importantly diminishes by a very high investment in innovation. This is surprising since one may attend that, to give a competitive advantage to his firm, each regulator reduces the emission-tax and increases the R&D subsidy, when markets are opened to competition. In Ben Youssef (2009) we found a similar result which is due to the transboundary pollution externality.

When markets are opened to international trade, competition of firms on the common market incites each regulator, through the use of the emission-tax and R&D subsidy, to increase his production to get a higher share of the common market, and this forces him to decrease his emission ratio by increasing the R&D level to have less pollution with respect to the status quo in innovation. However, since the marginal cost of innovation is increasing, the R&D level does not rise in a sufficiently quantity, which may increase pollution. Consequently, international competition increases production and innovation, which might reduce the profit of firms and increase pollution. The global consequence is a diminution of the social welfare when sufficiently large market sizes are opened to international trade. This last result contrasts with the one obtained in Ben Youssef (2009) where we showed that international competition improves the social welfare when market sizes are large enough i.e. the marginal damage of pollution is low enough.

The paper has the following structure. Section 2 presents the basic model when markets are separated. Section 3 treats the case where markets are opened to international competition. Section 4 compares the non-cooperative socially optimal values given by the two market regimes, and section 5 concludes. Finally, in an appendix we give the proofs of the propositions.

2. Separated markets

Our symmetric model consists of two countries and two firms. Firm *i*, located in country *i*, is a regional monopoly producing good *i* in quantity q_i which is sold on the home market having the following inverse demand function $p_i = a - 2q_i, a > 0$. Thus, the size of each market is equal to a/2.

As firm *i* is a regional monopoly that pollutes the domestic environment, it should be regulated. The regulator uses three types of instruments: an emission-tax per-unit of pollution t_i^a to induce the socially optimal levels of production and pollution, a subsidy per-unit of R&D level r_i^a to induce the socially optimal levels of R&D and emission/output ratio, and a lump sum tax on profit L_i^a. If this latter is negative, this signifies that the firm receives a lump sum subsidy from the regulator. The value of L_i^a is as such that the net profit of the firm will be at least equal to its reservation utility level which we assume to be equal to zero. Indeed, because of the positive marginal social cost of public funds, leaving the firm with a positive net profit is not socially optimal. Thus, the regulator chooses the socially optimal per-unit emission-tax and R&D subsidy in the first stage, given the reaction of the firm which will choose its optimal levels of R&D and production in the second and third stages, respectively. Therefore, by backward calculations up to the beginning of the game, we determine the three-stage subgame-perfect Nash equilibrium.

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, where k>0 is an investment cost parameter.

The profit of firm i is $\Pi_i^a = p_i(q_i)q_i - \theta q_i - kx_i^2$, where θ>0 is the marginal cost of production.

The emission per-unit of good produced of firm i is[1] $e_i = 1 - x_i$, $0 < x_i < 1$.

Thus, the emission of pollution of firm i is $E_i = (1 - x_i)q_i$.

The profit net of taxes and subsidies of firm i is $V_i^a = \Pi_i^a - t_i^a E_i + r_i^a x_i$, and its net profit is $U_i^a = V_i^a - L_i^a$.

Damages caused to country i are purely local:[2] $D_i = \alpha E_i$, where α>0 is the marginal disutility of pollution. We use a linear damage function, as many authors among which Péchoux and Pouyet (2003) and Ludema and Takeno (2007), to avoid too hard computations.

The production of q_i engenders a consumer surplus in country i equal to $CS_i^a = \int_0^{q_i} p_i(z)dz - p_i(q_i)q_i = q_i^2$.

Transfers to firms are supposed to be socially costly. We denote the marginal social cost of public funds by λ>0, which means that collecting 1$ from the firm costs λ$ to the regulator.[3] Thus, the consumer welfare of country i is equal to the consumer surplus, minus damages of pollution and the total monetary transfer to firm i which is adjusted by (1+λ) to account for the social cost of transfers:

$$W_i^a = CS_i^a(q_i) - D_i(q_i, x_i) - (1+\lambda)(-t_i^a E_i + r_i^a x_i - L_i^a)$$

The social welfare of a country is equal to the consumer welfare plus the net profit of the domestic firm:

$$S_i^a = W_i^a + U_i^a = CS_i^a(q_i) - D_i(q_i, x_i) + (1+\lambda)\Pi_i^a(q_i, x_i) - \lambda U_i^a \qquad (1)$$

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[1]We suppose that there is no R&D spillovers between firms. See D'Aspremont and Jacquemin (1988) for more information on this topic.

[2]In this paper, we do not consider transboundary pollution.

[3]See Ballard et al. (1985) and Laffont (1994) for more information on this subject.

Expression (1) will be used to determine the socially-optimal levels of production and R&D.

2.1. The reaction of firms

By backward induction, the firm maximizes in the third stage its profit net of taxes and subsidies, and not its net profit because it has no control on the lump sum tax, with respect to its production to get the optimal production in function of the R&D level, the per-unit emission-tax and the per-unit R&D subsidy. Then, in the second stage, the firm maximizes its profit net of taxes and subsidies with respect to its R&D level to get the optimal innovation level in function of the per-unit emission-tax and the per-unit R&D subsidy.

The first order condition of the firm's third stage is $\frac{\partial V_i^a}{\partial q_i} = 0$ (2)

The resolution of (2) gives:

$$q_i^{*a} = \frac{a - \theta - t_i^a (1 - x_i)}{4} \tag{3}$$

The first order condition of the firm's second stage is:

$$\frac{dV_i^a}{dx_i} = \frac{\partial q_i^{*a}}{\partial x_i} \frac{\partial V_i^a}{\partial q_i} + \frac{\partial V_i^a}{\partial x_i} = 0 \tag{4}$$

At the equilibrium, by using (2), equation (4) is simplified and, by using (3), its solution is:

$$x_i^{*a} = \frac{(a - \theta - t_i^a) t_i^a + 4 r_i^a}{8k - (t_i^a)^2} \tag{5}$$

The second order condition of the firm's second stage is verified at the equilibrium iff:

$$k > \frac{(t_i^a)^2}{8} \tag{C.1}$$

2.2. The optimal per-unit emission-tax and subsidy

In the first stage, each regulator i maximizes his social welfare, given by (1), with respect to t_i^a, r_i^a and U_i^a, under the rationality constraint of firm i. We allow ourselves to express the regulator's problem in function of U_i^a rather than L_i^a

because these latter are one-to-one related. Since the reservation utility level of firms is assumed to be equal to zero, the regulator chooses the lump sum tax on profit so that the net profit of his firm is nil (U_i^a=0). Therefore, the social welfare of country *i* becomes:

$$S_i^a(q_i, x_i) = CS_i^a(q_i) - D_i(q_i, x_i) + (1+\lambda)\Pi_i^a(q_i, x_i) \tag{6}$$

This social welfare function differs from the one defined in Ben Youssef (2009) because it gives a higher weight to the profit of the domestic firm, with respect to the consumer surplus and the damages caused by pollution. Consequently, strategic trade policy considerations are greater in the present paper.

To avoid difficult computations, the regulator does not look directly for the socially optimal per-unit emission-tax and per-unit R&D subsidy in the first stage. He maximizes, respectively in the third and second stages, his social welfare given by (6) with respect to the production quantity and the R&D level. Then, by equalizing the socially optimal quantities obtained to those chosen by the firm, he determines the socially optimal per-unit emission-tax and per-unit R&D subsidy. Therefore, the model is resolved as if it was a two-stage one.

The first order condition of the regulator's third stage is $\dfrac{\partial S_i^a}{\partial q_i} = 0$ (7)

The resolution of (7) gives:

$$\hat{q}_i^a = \frac{\alpha x_i + (1+\lambda)(a-\theta) - \alpha}{2(1+2\lambda)} \tag{8}$$

The first order condition of the regulator's second stage is:

$$\frac{dS_i^a}{dx_i} = \frac{\partial \hat{q}_i^a}{\partial x_i}\frac{\partial S_i^a}{\partial q_i} + \frac{\partial S_i^a}{\partial x_i} = 0 \tag{9}$$

Using (7) and (8), the solution of (9) is:

$$\hat{x}_i^a = \alpha \frac{(1+\lambda)(a-\theta) - \alpha}{4(1+\lambda)(1+2\lambda)k - \alpha^2} \tag{10}$$

The socially optimal level of R&D increases with the market size to avoid important damages to the environment because of the increase of production.

To ensure that the numerator of (10) is positive,[4] we need that :[5]

$$(1+\lambda)(a-\theta)>\alpha \Leftrightarrow (1+\lambda)a>\alpha+(1+\lambda)\theta \quad \text{(C.2)}$$

Condition (C.2) means that the market sizes are sufficiently high with respect to α, θ and λ. Also, it means that α is sufficiently low with respect to a, θ, and λ. Indeed, when the marginal disutility of pollution is high, the investment in R&D might be too high if it does not cost much, leading to a negative emission ratio, which has no economic meaning.

By equalizing the R&D level chosen by firms given by (5) to the socially optimal one given by (10), we get:

$$r_i^a = \frac{\left[8k-(t_i^a)^2\right]\hat{x}_i^a-(a-\theta-t_i^a)t_i^a}{4} \quad (11)$$

Then, by equalizing the production level chosen by firms given by (3) to the socially optimal one given by (8), we get:

$$t_i^a = \frac{a-\theta-4\hat{q}_i^a}{1-\hat{x}_i^a} \quad (12)$$

From (8), (10) and (12), we have: $\lim_{k\to+\infty} t_i^a = \frac{2\alpha-(a-\theta)}{1+2\lambda}$ (13)

The above limit is a finite number, then condition (C.1) can always be satisfied by choosing k sufficiently high, and the emission-tax is positive when a-θ<2α.

Also, from (10), (11) and (13), we have: $\lim_{k\to+\infty} r_i^a = \frac{\left[(1+\lambda)(a-\theta)-\alpha\right]^2}{2(1+\lambda)(1+2\lambda)^2}>0$ (14)

This implies that, when k is high enough, $r_i^a > 0$.

3. Common market

When markets are opened to international competition, firms produce perfect substitute goods sold on the common market of the two countries having the

[4]Alternatively, we can require that the numerator and denominator of (10) are negative i.e. that the market sizes and k are low enough. However, this would be incompatible with the concavity condition of the regulator's second stage.

[5]Condition (C.2) and k sufficiently high with respect to a, θ, α and λ guarantee that $\hat{q}_i^a > 0$, $0 < \hat{x}_i^a < 1$, and the second order condition of the regulator's second stage at the equilibrium.

following inverse demand function $p = a - (q_i + q_j)$. The size of the unique market is equal to a.

The firms profits are $\Pi_i^{cm} = p(q_i + q_j)q_i - \theta q_i - kx_i^2$.

The emission-tax per-unit of pollution is t_i^{cm} and the subsidy per-unit of R&D level is r_i^{cm}.

The profit net of taxes and subsidies of firm *i* is $V_i^{cm} = \Pi_i^{cm} - t_i^{cm} E_i + r_i^{cm} x_i$, and its net profit is $U_i^{cm} = V_i^{cm} - L_i^{cm}$.

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

The social welfare of country *i* can be written as:

$$S_i^{cm} = CS_i^{cm}(q_i, q_j) - D_i(q_i, x_i) + (1+\lambda)\Pi_i^{cm}(q_i, q_j, x_i) - \lambda U_i^{cm} \tag{15}$$

As for the autarky case, firms have a zero net profit, and the social welfare of country *i* becomes:

$$S_i^{cm}(q_i, q_j, x_i) = CS_i^{cm}(q_i, q_j) - D_i(q_i, x_i) + (1+\lambda)\Pi_i^{cm}(q_i, q_j, x_i) \tag{16}$$

3.1. The reaction of firms

Each firm maximizes its profit net of taxes and subsidies with respect to its production and R&D level in the third and second stages, respectively.

The first order conditions of the firms third stage are $\frac{\partial V_i^{cm}}{\partial q_i} = \frac{\partial V_j^{cm}}{\partial q_j} = 0$ (17)

The resolution of system (17) gives:

$$q_i^{*cm} = \frac{a - \theta - 2t_i^{cm}(1 - x_i) + t_j^{cm}(1 - x_j)}{3} \tag{18}$$

The symmetric expression of (18) is:

$$q_i^{*cm} = \frac{a - \theta - t_i^{cm}(1 - x_i^{*cm})}{3} \tag{19}$$

The first order condition of the firm's second stage is:

$$\frac{dV_i^{cm}}{dx_i} = \frac{\partial q_i^{*cm}}{\partial x_i}\frac{\partial V_i^{cm}}{\partial q_i} + \frac{\partial q_j^{*cm}}{\partial x_i}\frac{\partial V_i^{cm}}{\partial q_j} + \frac{\partial V_i^{cm}}{\partial x_i} = 0 \tag{20}$$

At the equilibrium, because of (17), equation (20) is simplified. By using (18) for the partial derivatives, and then (19), the symmetric[6] solution of (20) is:

$$x_i^{*cm} = \frac{4(a-\theta-t_i^{cm})t_i^{cm} + 9r_i^{cm}}{18k - 4(t_i^{cm})^2} \tag{21}$$

The second order condition of the firm's second stage is verified at the equilibrium iff:

$$k > \frac{4}{9}(t_i^{cm})^2 \tag{C.3}$$

3.2. The optimal per-unit emission-tax and subsidy

Rather than directly looking for the socially optimal per-unit emission-tax and per-unit R&D subsidy in the first stage, each regulator determines the socially optimal production and innovation levels in the third and second stages, respectively.

The first order conditions of the regulators third stage are $\frac{\partial S_i^{cm}}{\partial q_i} = \frac{\partial S_j^{cm}}{\partial q_j} = 0$ (22)

The solution of system (22) is :

$$\hat{q}_i^{cm} = \frac{\left[(3+4\lambda)x_i - (1+2\lambda)x_j\right]\alpha + 2(1+\lambda)\left[(1+\lambda)(a-\theta)-\alpha\right]}{2(1+\lambda)(2+3\lambda)} \tag{23}$$

The symmetric expression of (23) is:

$$\hat{q}_i^{cm} = \frac{\alpha\hat{x}_i^{cm} + (1+\lambda)(a-\theta) - \alpha}{2+3\lambda} \tag{24}$$

The first order condition of the regulator's second stage is:

$$\frac{dS_i^{cm}}{dx_i} = \frac{\partial\hat{q}_i^{cm}}{\partial x_i}\frac{\partial S_i^{cm}}{\partial q_i} + \frac{\partial\hat{q}_j^{cm}}{\partial x_i}\frac{\partial S_i^{cm}}{\partial q_j} + \frac{\partial S_i^{cm}}{\partial x_i} = 0 \tag{25}$$

Using (22), (23) for the partial derivatives and then (24), the symmetric solution of (25) is:[7]

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[6]We look for the symmetric equilibria because the model is symmetric and computations are easier. We have the right to look for the symmetric equilibria at this second stage, rather than the first one, because the backward resolution of the game is stopped at the second stage.

[7]Condition (C.2) and k sufficiently high with respect to a, θ, α and λ, guarantee that $\hat{q}_i^{cm} > 0$, $0 < \hat{x}_i^{cm} < 1$, and the second order condition of the regulator's second stage at the equilibrium.

$$\hat{x}_i^{cm} = \frac{(4+11\lambda+8\lambda^2)\left[(1+\lambda)(a-\theta)-\alpha\right]\alpha}{4(1+\lambda)^2(2+3\lambda)^2 k-(4+11\lambda+8\lambda^2)\alpha^2} \tag{26}$$

By equalizing the R&D level chosen by firms given by (21) to the socially optimal one given by (26), we get:

$$r_i^{cm} = \frac{\left[18k-4(t_i^{cm})^2\right]\hat{x}_i^{cm}-4(a-\theta-t_i^{cm})t_i^{cm}}{9} \tag{27}$$

Then, by equalizing the production level chosen by firms given by (19) to the socially optimal one given by (24), we get:

$$t_i^{cm} = \frac{a-\theta-3\hat{q}_i^{cm}}{1-\hat{x}_i^{cm}} \tag{28}$$

From (24), (26) and (28), we deduce: $\lim_{k\to+\infty} t_i^{cm} = \frac{3\alpha-(a-\theta)}{2+3\lambda}$ (29)

This last limit is a finite number, then condition (C.3) can always be satisfied when k is sufficiently high, and the emission-tax is positive when a-θ<3α.

From (26), (27) and (29), we get:

$$\lim_{k\to+\infty} r_i^{cm} = \frac{\left[(1+\lambda)(a-\theta)-\alpha\right]\left[8(1+\lambda)^2(a-\theta)-3(4+5\lambda)\alpha\right]}{6(1+\lambda)^2(2+3\lambda)^2} \tag{30}$$

When k and a are sufficiently high, equality (30) and (C.2) show that r_i^{cm} >0.

4. Separated markets versus common market

In what follows, we suppose that condition (C.2) is verified, meaning that the market sizes are sufficiently high with respect to α, θ and λ, and that k is high enough.

As mentioned before, each regulator determines the non-cooperative socially optimal levels of production and R&D and, by means of the per-unit emission-tax and the per-unit R&D subsidy, pushes his firm to implement them.

Proposition 1. *Opening markets to international trade:*

i) Increases the R&D level and production, and decreases the emission/output ratio.

ii) Increases pollution when α is sufficiently high.

iii) Reduces the social welfare.

Competition on the common market leads to a higher level of production because of the strategic substituability of goods in the profit functions of firms. Such a raise of production is accompanied by a decrease of the emission ratio, realized by increasing the R&D level, in order to cause less environmental damages with respect to the status quo in innovation.

Besides, when the marginal damage of pollution is high enough, the R&D level provided to internalize pollution is important and the emission ratio is low. Thus, when markets are opened to international trade, the emission/output ratio slightly decreases because the marginal cost of R&D is increasing, whereas production significantly increases, leading to an increase of pollution.

Such an expansion of the levels of production and R&D might reduce the profit of firms, particularly because the marginal cost of innovation is increasing, and raise pollution, leading to a social welfare diminution.

Proposition 2. *The per-unit emission-tax is higher in common market than in autarky, whereas the per-unit R&D subsidy is lower.*

Since pollution, when α is high enough, and R&D are greater in common market, one may think that the emission-tax is lower in common market, whereas the R&D subsidy is greater. Surprisingly, our results show the contrary. Indeed, when markets are opened to international trade, the regulator increases his per-unit emission-tax to avoid damages to his environment because competition incites firms to considerably expand their production and, therefore, pollution. However, he decreases the per-unit R&D subsidy to avoid that the profit of the domestic firm importantly diminishes by a very high investment in innovation as the marginal cost of innovation is increasing.[8]

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[8]Notice that, if λ was nil, then expressions (10), (26), (8), (24), (6) and (16) show that the socially optimal values of R&D, production, pollution and social welfare in autarky and common market would be equal. However, this

5. Conclusion

We develop a non-cooperative three-stage game played by two regulator-firm hierarchies in presence of costly public funds. We evaluate the impact of international competition.

The most important result of this paper is that free mobility of goods among countries increases the per-unit emission-tax and decreases the per-unit R&D subsidy. This is interesting because it goes against the standard intuition that each government reduces the emission-tax and increases the R&D subsidy in order to give a competitive advantage to his domestic firm.

We show that international competition leads to more production, more investment in R&D, and to a lower emission ratio. As a result, when the marginal disutility of pollution is sufficiently high, international trade increases pollution. Consequently, the social welfare is greater when markets are separated than when there is a common market.

These results have been shown in the case of sufficiently large market sizes, but it would be interesting to know what happens if market sizes are not too large.

A possible extension of this work is to introduce asymmetric information between each regulator and its respective firm concerning the production cost or the R&D activity. Incomplete information might change our results because competition of firms on the common market might reduce their informational rents and, therefore, might increase the social welfare.

Appendix

A) Proof of Proposition 1

i) Using expressions (10) and (26), we show that $\hat{x}_i^{cm} - \hat{x}_i^{a}$>0, which implies that $\hat{e}_i^{cm} < \hat{e}_i^{a}$.

Since $\hat{x}_i^{cm} > \hat{x}_i^{a}$, from expressions (8) and (24), we also have $\hat{q}_i^{cm} > \hat{q}_i^{a}$.

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assumption would not change the results concerning the per-unit emission-tax and the per-unit R&D subsidy (see the limits calculated at the end of the appendix).

ii) Consider the function $f(x) = (1-x)[\alpha x + (1+\lambda)(a-\theta) - \alpha]$.

Using expressions (8), (24) and $\hat{E}_i = (1-\hat{x}_i)\hat{q}_i$, we can verify that $\hat{E}_i^a = \dfrac{f(\hat{x}_i^a)}{2(1+2\lambda)}$ and

$\hat{E}_i^{cm} = \dfrac{f(\hat{x}_i^{cm})}{2+3\lambda}$.

We have: $f'(x) > 0 \Leftrightarrow x < x^1 = \dfrac{2\alpha - (1+\lambda)(a-\theta)}{2\alpha}$.

If (1+λ)(a-θ)<2α, then $f'(x) > 0, \forall x < x^1$ with $x^1 > 0$. Moreover, when k is high enough, expression (26) shows that $\hat{x}_i^{cm} < x^1$. Thus, f is strictly increasing on the interval $[\hat{x}_i^a, \hat{x}_i^{cm}]$.

Therefore, if (1+λ)(a-θ)<2α and k is high enough, then $0 < f(\hat{x}_i^a) < f(\hat{x}_i^{cm})$, implying that:

$$\hat{E}_i^{cm} = \frac{f(\hat{x}_i^{cm})}{2+3\lambda} > \frac{f(\hat{x}_i^a)}{2+3\lambda} > \frac{f(\hat{x}_i^a)}{2(1+2\lambda)} = \hat{E}_i^a$$

Thus, when α and k are high enough, opening markets to international trade increases pollution.

iii) Using expressions (6) and (16), the symmetric equilibrium social welfare of country *i* can be written as:

$$\hat{S}_i = -(1+2\lambda)(\hat{q}_i(\hat{x}_i))^2 + [\alpha\hat{x}_i + (1+\lambda)(a-\theta) - \alpha]\hat{q}_i(\hat{x}_i) - (1+\lambda)k\hat{x}_i^2$$

where $\hat{q}_i(\hat{x}_i)$ is expression (8) in the autarky case, or is expression (24) in the common market case.

Using expressions (8) and (24):

$$\hat{S}_i = d[\alpha\hat{x}_i + (1+\lambda)(a-\theta) - \alpha]^2 - (1+\lambda)k\hat{x}_i^2$$

where $d = d^a = \dfrac{1}{4(1+2\lambda)}$ in autarky, and $d = d^{cm} = \dfrac{1+\lambda}{(2+3\lambda)^2}$ in common market. It is easy to verify that $d^a > d^{cm}$.

Consider the function $g(x) = \dfrac{1+\lambda}{(2+3\lambda)^2}[\alpha x + (1+\lambda)(a-\theta) - \alpha]^2 - (1+\lambda)kx^2$.

We can easily verify that $\hat{S}_i^{cm} = g(\hat{x}_i^{cm})$.

Since k is supposed to be high enough, then $g'(x) < 0 \Leftrightarrow x > x^2 = \dfrac{[(1+\lambda)(a-\theta) - \alpha]\alpha}{(2+3\lambda)^2 k - \alpha^2}$.

Using the expression of $\hat{x}_i^a$ given by (10), we show that $\hat{x}_i^a - x^2$>0. Thus, *g* is strictly decreasing on the interval $[\hat{x}_i^a, \hat{x}_i^{cm}]$, and since $d^{cm} < d^a$, we have:

$$\hat{S}_i^{cm} = g(\hat{x}_i^{cm}) < g(\hat{x}_i^a) = d^{cm}\left[\alpha\hat{x}_i^a + (1+\lambda)(a-\theta) - \alpha\right]^2 - (1+\lambda)k(\hat{x}_i^a)^2 < \hat{S}_i^a$$

Therefore, opening markets to international trade reduces the social welfare.

B) Proof of Proposition 2

From (13) and (29), we have $\lim_{k\to+\infty} t_i^{cm} - t_i^a = \frac{(1+\lambda)(a-\theta)-\alpha}{(1+2\lambda)(2+3\lambda)} > 0$ because of condition (C.2). Therefore, $t_i^{cm} > t_i^a$ when k is high enough.

From (14), (30) and (C.2), $\lim_{k\to+\infty} r_i^{cm} - r_i^a$ has the sign of:

$$X = (1+\lambda)^2(a-\theta)(5\lambda^2 - 4\lambda - 4) - 3\lambda(11\lambda^2 + 15\lambda + 5)\alpha$$

By assuming[9] 0<λ<1.3, then $5\lambda^2 - 4\lambda - 4 < 0$ and X<0, implying that $r_i^{cm} < r_i^a$ when k is sufficiently high.

[9] Ballard et al. (1985) found that λ is between 0.17 and 0.56.

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