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Transboundary Pollution, R&D Spillovers, Absorptive Capacity and International Trade

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Abstract
In this paper, we consider a non-cooperative and symmetric three-stage game model composed by two regulator-firm hierarchies. By means of adequate emission taxes, original and absorptive research and development (R&D) subsidies we prove that regulators can reach the non-cooperative social optimum. In the presence of free R&D spillovers between countries, as well as the investment in absorptive research, the competition of firms on a common market helps non-cooperating countries to better internalize transboundary pollution. We find that in autarky and common market cases the investment in absorptive R&D leads to multiple non-cooperative equilibria, which may necessitate competing regulators to coordinate an equilibrium. Interestingly, opening markets to international trade increases the per-unit emission-tax and the per-unit original research subsidy. It causes a higher investment in original research and production, and a lower emission ratio.

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Keywords Transboundary pollution; R&D spillovers; absorptive capacity; international trade

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1 Introduction

The aim of this paper is to characterize the socially optimal production, investment in inventive research and development (R&D) and absorptive capacity. We used tax and subsidies rates in a game played by two regulator-firm hierarchies with the negative externality and transboundry pollution which usually does not lead non-cooperating countries to the Pareto-optimality. However, some authors showed that non-cooperating governments can reach the first best under some conditions (Hoel 1997, Zagonari 1998). By developing a static two country, two-good general equilibrium model, Takarada (2005) examnated the welfare effects of the transfer of pollution abatement technology when cross-border pollution exists. He derived and interpreted the conditions under which technology transfer enriches the donor and the recipient. By different environmental policy instruments for promoting technological change in pollution control such as direct controls, emissions subsidies, emissions taxes, free marketable permits and auctioned marketables permits, Milliman and Prince (1989) showed that emissions taxes and auctioned permits provied the highest firm incentives to promote technological change. Jung et al. (1996) extended this approach to a heterogenous industry. Stranlund (1997) considered public aid to encourage the adoption of superior emission control technologies combined with monitoring. This strategy is attractive when monitoring is difficult because the sources of pollution are widely dispersed or the emissions are not easily measured as in non point pollution problems. Technological aid reduces the direct enforcement effort necessary for firms to reach the compliance goal.

Farzin and Kort (2000) examineted the effect of a high pollution tax rate on abatement investment both under full certainty and when the timing or the size of tax increase is uncertain. We showed that a higher pollution tax encourages abatment investment if it does not exceed a certain threshold rate. Liao (2007) investigated the non-cooperative and jointly optimal R&D subsidy policies of two exporting countries in the presence of international technology spillovers. He showed that when spillovers are low (high), the R&D game exhibits a negative (positive) externality, so the jointly optimal policy is to tax (subsidize) R&D. Using a non-cooperative and symetric three-stage game played by two regulator-firm hierarchies, Ben Youssef (2009) showed that free R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transfrontier pollution. Surprisingly, international competition increase the per-unit emissions-tax and decreases the per-unit R&D subsidy. Conrad (1993) constructed a model of international duopoly with negative externalities in production in which optimal environmental policy responses to foreign emissions tax and subsidy programs can be calculated. However, he did not consider R&D possibilities and took the context of international market. Also, with a model of imperfectly competitive international markets and without pollution, Spencer and Brander (1983) showed that there are national incentives to subsidize R&D if export subsidies are not available.

R&D activities generate innovations and develop the firm's ability to identify, assimilate, and exploit knowladge from the environment, for this Cohen and Levinthal (1989) were the first to introduce the idea of absorptive capacity in the cost reduction R&D literature. Contrary to D'Aspremont and Jacquemin (1988, 1990) and Kamien et al. (1992), where R&D spillovers are assumed exogenous and cost free, Poyago-Theotoky (1999) showed that, when spillovers of information are endogenized, non-cooperative firms never disclose any of their information, whereas they will always fully share their information when they cooperate in R&D. Kamien and Zang (2000) modeled a firm's effective R&D level that reflects how both its R&D approach (firm specific or general) and R&D level influence its absorptive capacity. Leahy and Neary (2007) specified a general model of the absorptive capacity process and showed that costly absorption both raises the effectiveness of own R&D and lowers the effective spillover coefficient. This weakens the case for encouraging research joint ventures, even if there is complete information sharing between firms. Milliou (2009) showed that the lack of full appropriability can lead to an increase in R&D investments. Hammerschmidt (2009) distinguished between two types of R&D: inventive (or original) R&D that generates new knowledge and absorptive R&D that allows a firm to benefit from the inventive R&D conducted by others. She found that firms will invest more in R&D to strengthen absorptive capacity when the spillover parameter is higher.

Ben Youssef and Zaccour (2009) were the first to integrate into the same model absorptive R&D and pollution control. They have compared the socially optimal levels of original and absorptive research, and the socially optimal subsidies for both types of R&D. There are no free R&D spillovers between firms, Ben Youssef (2010) showed that the investment in absorptive research enables non-cooperating regulators to better internalize transboundary pollution. In contrast, Ben Youssef (2009) showed that free R&D spillovers and the competition of firms on a common market help non-cooperating countries to better internalize transboundary pollution.

The difference in our model and the model of Ben Youssef (2009) is to integrate the investment in absorptive research. We wish to show how R&D spillovers, the investment in absorptive research and the competition of firms on the common market help non-cooperating countries to internalize transboundary pollution.

We consider a non-cooperative and symmetric three-stage game consisting of two identical regulator-firm hierarchies. Each firm produces one good sold on the domestic market in the third stage and they can invest in original and absorptive research which directly reduces its emission/output ratio, in the second stage. In the first stage, regulators announce non-cooperatively their per-unit emission tax and R&D subsidies and them aims are maximizing his social welfare function to reach the non-cooperative social optimum. This game is solved backward to get a sub-game perfect Nash equilibrium.

We show that regulators can induce their firms to implement the non-cooperative socially optimal levels of production and R&D by using three regulatory instruments, which are a per-unit emission tax, a per-unit original research subsidy and a per-unit absorptive research subsidy. Moreover, in autarky and common markets cases, the investment in absorptive R&D may leads to a multiplicity of subgame perfect Nash equilibria necessitating the coordination on an equilibrium, which constitutes an incentive for non-cooperating countries to cooperate.

Interestingly, we show that without R&D spillovers and the ability to absorb $(l = 0, \beta = 0)$, transboundary pollution is completely not internalized in the autarky regime. The higher are the ability to absorb and the R&D spillovers, the greater is the proportion of transboundary pollution internalized by non cooperating countries. Moreover, opening markets to international trade help countries to better internalize transboundary pollution through firms competition on the common market, which are realized by an increase in the level of the original and absorptive research. Consequently, the emission ratio is lower, enabling states to produce more in common market.

The paper has the following structure. In Section 1, we introduce the model. Section 2 presents the basic model in autarky, resolves it and exhibits the role of the R&D spillovers and the absorptive capacity in 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 transbounder pollution, in Section 4 we compare the non-cooperative socially optimal values in autarky and common markets, and in section 5 we conclude. An appendix contains some proofs.

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 on the domestic market having the following inverse demand function $p_i = a - bq_i$ where $a, b > 0$. One reason for the market structure used is that the markets of the industries engaged in large investments in R&D are usually oligopolistic.

The production process generates pollution and firms can invest in R&D in order to lower their fixed emission/output ratio. We distinguish between inventive or original research, denoted by x_i^o, which directly reduces the emission ratio and costs $k^o\left(x_i^o\right)^2$, where $k^o > 0$, and absorptive research, denoted by x_i^a, which enables a firm to capture part of the original research made by the other one, and costs $k^a\left(x_i^a\right)^2$, where $k^a > 0$.

The innovation activity carried out by firms is caracterized by positive externalities which imply that a proportion β of each firm's R&D level gratuitously spillovers to the other firm and by absorptive capacity is implicitly assumed that the ability to absorb spillovers from other firm. The effective R&D level of firm i is $x_i = x_i^o + (\beta + l x_i^a) x_j^o$,where $0 \leq \beta < 1$ and $l > 0$.

By normalizing the emission per unit of production to one without innovation, the emission/output ratio of firm i is $e_i = 1 - x_i^o - (\beta + l x_i^a) x_j^o$ and its emission of pollution is $E_i = \left[1 - x_i^o - (\beta + l x_i^a) x_j^o\right] q_i$.

Since firm i is a regional monopoly that pollutes the domestic environment, it is regulated. Each regulator behaves non-cooperatively and maximizes his own social welfare function by using three regulatory instruments: an emission tax per unit of pollution t_i^f to induce the noncooperative socially optimal levels of production and pollution, a subsidy per unit of original R&D level r_i^{of} and a subsidy per unit of absorptive R&D level r_i^{af} to induce the non-cooperative socially optimal levels of effective R&D and emission/output ratio. Therefore, each regulator chooses the non-cooperative socially optimal per-unit emission tax and per-unit R&D subsidies in the first stage given that the reaction of his firm which is it chooses its optimal levels of R&D and production in the second and third stages, respectively. This three-stage game is solved backward to get a the subgame perfect Nash equilibrium.

denoting the marginal cost of production by $\theta > 0$, the profit of firm i is $\pi_i^f = p_i(q_i) q_i - \theta q_i - k^o (x_i^o)^2 - k^a (x_i^a)^2$, and its profit net of taxes and subsidies is $V_i^f = \pi_i^f - t_i^f E_i + r_i^{of} x_i^o + r_i^{af} x_i^a$.

Conjecture 1 *We conjoncture that* $\lim_{k^o, k^a \to +\infty} x_i^{of} = \lim_{k^o, k^a \to +\infty} x_i^{af} = 0$

This conjecture is logical because when the investment cost parameters are relatively very high, it is socially optimal to not invest in R&D.

Transboundary pollution is also a negative externality among countries. Thus, the damages caused to country i are $D_i = \alpha E_i + \gamma E_j$ where $\alpha > 0$ is the marginal damage of the domestic pollution, and $\gamma > 0$ is the marginal damage of the foreign pollution.[1]

The consumer surplus in country i engendered by the consumption of q_i^f is $CS_i^f = \int_0^{q_i} p_i(u)\,du - p_i(q_i)\,q_i = \frac{b}{2}q_i^2.$

The social welfare of a country is defined as the consumer surplus, minus damages and subsidies, plus taxes and the net profit of the domestic firm, and is equal, after simplifications, to:

$$S_i^f\left(q_i, q_j, x_i^o, x_i^a, x_j^o, x_j^a\right) = CS_i^f - D_i + \pi_i^f \tag{1}$$

Notice that taxes and subsidies do not appear in the social welfare function because the tax diminished from the firm's profit is added to the consumer welfare, and the subsidies added to the firm's profit are diminished from the

[1] 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 $\alpha = d(1-c)$ and $\gamma = dc$, where $0 < c < 1$ 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 whole pollution. To explain how transfrontier pollution can be internalized, we separate the negative effect of the foreign pollution from the one of at home pollution by separating γ and α.

consumer welfare.

2.1 The reaction of firms

The regulator announced in the first stage the per-unit emission tax and the per-unit R&D subsidies, the firm reacts by choosing its optimal research and production levels in the second and third stages, respectively. By backward induction, the firm maximizes in the third stage its net profit with respect to its production level, and in the second stage, it maximizes its net profit with respect to its R&D levels.

The first order condition of firm i third stage is:

$$\frac{\partial V_i^f}{\partial q_i} = 0 \tag{2}$$

The resolution of (2) gives:

$$q_i^{*f} = \frac{a - \theta - t_i \left[1 - x_i^o + \left(\beta + l x_i^a\right) x_i^o\right]}{2b} \tag{3}$$

We deduce the following:

$$\frac{\partial q_i^{*f}}{\partial x_i^o} = \frac{t_i}{2b}; \frac{\partial q_i^{*f}}{\partial x_i^a} = \frac{t_i l x_j^o}{2b}$$
$$\frac{\partial q_i^{*f}}{\partial x_j^o} = \frac{t_i \left(\beta + l x_i^a\right)}{2b}; \frac{\partial q_i^{*f}}{\partial x_j^a} = 0$$

Consider the case of a positive emission tax. When a firm increase its level of original or a absorptive research, its emissions/output ratio decrease enabling it to expand its production. When the competing firm increase its original research, this has a positif effect on the production of the firm: because of R&D spillovers and absorptive capacity, the emission ratio of firm decrease enabling it to expend its production.

The symmetric optimal production level for each firm is obtained from expression (3):

$$q_i^{*f} = \frac{a - \theta - t_i \left[1 - \left(1 + \beta + l x_i^a\right) x_i^o\right]}{2b} \tag{4}$$

The first-order conditions of firm i second stage are [2] :

$$\frac{dV_i^f}{dx_i^o} = \frac{\partial q_i^{*f}}{\partial x_i^o} \frac{\partial V_i^f}{\partial q_i} + \frac{\partial V_i^f}{\partial x_i^o} = 0 \tag{5}$$

and

$$\frac{dV_i^f}{dx_i^a} = \frac{\partial q_i^{*f}}{\partial x_i^a} \frac{\partial V_i^f}{\partial q_i} + \frac{\partial V_i^f}{\partial x_i^a} = 0 \tag{6}$$

At the equilibrium, by using (2), equations (5) and (6) are simplified, and the symmetric [3] solutions are given by the following equations system :

[2] The second-order conditions are verified in the appendix when k^o and k^a are high enough.

[3] The model is symmetric for this we look for the symmetric equilibrium. Further, as will be made clear in the following section, the backward resolution of the game is stopped at the second stage, which explains why it is appropriate to look for symmetric equilibria at this second stage.

$$t_i^f q_i^{*f} + r_i^{of} - 2k^o x_i^o = 0 \tag{7}$$

and

$$t_i^f l x_i^o q_i^{*f} + r_i^{af} - 2k^a x_i^a = 0 \tag{8}$$

where q_i^{*f} is given by (4).

2.2 The Non-Cooperative Socially Optimal Emission Tax and R&D Subsidies

At the first stage, each regulator i maximizes his social welfare, given by (1), with respect to t_i^f, r_i^{of} and r_i^{af} which are the choice variables. However, this direct method is not easy to do if the regulator looks directly for the optimal per-unit emission tax and per-unit R&D subsidies. Therefore, we will use a simpler method. Indeed, the regulator maximizes, respectively in the third and second stages, his social welfare with respect to the production quantity and the R&D levels which become the new choice variables. Then, by equalizing the socially optimal quantities obtained to those chosen by his firm, he determines the socially optimal per-unit emission tax and per-unit R&D subsidies. The model is resolved as if it was a two-stage game.

Expression (1) can be written :

$$\begin{aligned} S_i^f = \frac{b}{2} q_i^2 - \alpha \left[1 - x_i^o + (\beta + l x_i^a) x_j^o \right] q_i - \gamma \left[1 - x_j^o - (\beta + l x_j^a) x_i^o \right] q_j \\ + (a - b q_i) q_i - \theta q_i - k^o x_i^{o2} - k^a x_i^{a2} \end{aligned} \tag{9}$$

In the third stage, when regulator i chooses his socially optimal production level , the parameter γ is eliminated by the derivation of S_i^f with respect to q_i. Thus, the pollution coming from country j is completely not internalized. This is general for static models with a damage function linear with respect to the whole pollution, or a separable one with respect to the pollution remaining at home and the one received from other countries. However, when he chooses his optimal level of inventive research in the second stage, the negative transboundary externality is partially internalized if the learning parameter and the R&D spillovers are non-nil. The higher the absorptive parameter and R&D spillovers are, the greater proportion of transboundary pollution is internalized.

The first-order condition of regulator i third stage is:

$$\frac{\partial S_i^f}{\partial q_i} = 0 \tag{10}$$

The resolution of (10) gives

$$\hat{q}_i^f = \frac{a - \theta - \alpha \left[1 - x_i^o - (\beta + l x_i^a) x_j^o\right]}{b} \tag{11}$$

The symmetric expression of (11) is

$$\hat{q}_i^f = \frac{a - \theta - \alpha \left[1 - (1 + \beta + l x_i^a) x_i^o\right]}{b} \tag{12}$$

A sufficient condition for the symmetric production quantities to be positive is

$$a > \theta + \alpha \iff a - \theta > \alpha \tag{13}$$

Thus, the marginal domestic damage cost of pollution is lower than the maximum willingness to pay for the good minus its marginal cost of production.

The first-order conditions of regulator i second stage are [4]

$$\frac{dS_i^f}{dx_i^o} = \frac{\partial \hat{q}_i}{\partial x_i^o}\frac{\partial S_i^f}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_i^o}\frac{\partial S_i^f}{\partial q_j} + \frac{\partial S_i^f}{\partial x_i^o} = 0 \tag{14}$$

and

$$\frac{dS_i^f}{dx_i^a} = \frac{\partial \hat{q}_i}{\partial x_i^a}\frac{\partial S_i^f}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_i^a}\frac{\partial S_i^f}{\partial q_j} + \frac{\partial S_i^f}{\partial x_i^a} = 0 \tag{15}$$

At the equilibrium, by using (10) , equations (14)-(15) is simplified , and the symmetric solutions are given by the following equations system

$$\begin{aligned} & b\left[\alpha + \gamma\left(\beta + lx_i^{af}\right)\right]\hat{q}_i - \alpha\gamma\left(\beta + lx_i^{af}\right) \\ & \times\left[1 - \left(1 + \beta + lx_i^{af}\right)x_i^{of}\right] - 2bk^o x_i^{of} = 0 \end{aligned} \tag{16}$$

and

$$\alpha l x_i^{of}\hat{q}_i^f - 2k^a x_i^{af} = 0 \tag{17}$$

[4] The second-order conditions are verified in the appendix when k^o and k^a are high enough.

When we replace $\hat{q}_i^f$ by its symmetric expression, the equations (16)- (17) become:

$$(a-\theta)\left[\alpha+\gamma\left(\beta+lx_i^{af}\right)\right]-\alpha\left[1-\left(1+\beta+lx_i^{af}\right)x_\iota^{of}\right] \times\left[\alpha+2\gamma\left(\beta+lx_i^{af}\right)\right]-2bk^o x_i^{of}=0 \tag{18}$$

and

$$\alpha l x_i^{of}\left[a-\theta-\alpha+\alpha(1+\beta+lx_i^{af})x_i^{of}\right]-2bk^a x_i^{af}=0 \tag{19}$$

The non-linear equations system (18) and (19), confirms the fact that when the learning parameter and the R&D spillovers are nil ($l=0,\beta=0$), transboundary pollution is completely not internalized since γ disappears from (18). Consequently, we can obtain the expressions of $\hat{x}_i^{of}$ and $\hat{x}_i^{af}$ explicitly. The higher l and/or β is, the greater proportion of transboundary pollution is internalized. Thus, we can deduce the following proposition.

Proposition 2 *The R&D spillovers and the investment in absorptive research enable non-cooperating countries to better internalize transboundary pollution. The higher β and/or the ability to absorb are, the greater is the proportion of transboundary pollution internalized.*

Solving of the non-linear equations system (18)-(19) gives the symmetric socially optimal R&D levels denoted by $\hat{x}_i^{of}$ and $\hat{x}_i^{af}$. Accordingly, we can not have the explicit solutions. For this reason we get the followind proposition.

Proposition 3 *When k^o and k^a are sufficiently high, there are at least one* *and at most five couples of real solutions* $\hat{x}_i^{of} > 0$ *and* $\hat{x}_i^{af} > 0$ *that solve the non-linear equations system given by* (18) *and* (19).

PROOF. See the appendix.

The above proposition shows the possibility of multiple symmetric equilibria maximizing the social walfare. In this case, non-cooperating regulators have to coordinate on an equilibrium, which constitutes an incentive for them to fully cooperate. Therefore, the possibility to invest in absorptive research may give incentives to cooperate.

When k^o and k^a are high enough, the condition (13) and the conjecture guarantee that the socially optimal levels of research, production, and pollution are positive, and that $0 \leq \beta + lx_i^a \leq 1$.

Since the emission tax and the R&D subsidies are set to incite firms to reach the socially optimal production and research levels which are $\hat{q}_i^f$, $\hat{x}_i^{of}$ and $\hat{x}_i^{af}$, then from equations (4), (7), and (8) we have the optimal emission tax and R&D subsidies :

$$t_i^f = \frac{a - \theta - 2b\hat{q}_i}{1 - (1 + \beta + l\hat{x}_i^{af})\hat{x}_i^{of}} \tag{20}$$

and

$$r_i^{of} = 2k^o\hat{x}_i^o - t_i^f\hat{q}_i^f \tag{21}$$

and

$$r_i^{af} = 2k^a \hat{x}_i^a - t_i^f l \hat{x}_i^o \hat{q}_i^f \tag{22}$$

Proposition 4 *In the autarky regime, the regulator can induce their firms to reach the noncooperative socially optimal levels of production and R&D by using the three regulatory instruments, which are a per-unit emission tax, a per-unit original research subsidy, and a per-unit absorptive research subsidy.*

This proposition shows that necessity of the three regulatory instruments to incentive for firms to implement the socially optimals levels of production and R&D.

By using the conjecture, the expressions (12) and (20), we obtain:

$$\lim_{k^o, k^a \to +\infty} t_i^f = 2\alpha - (a - \theta) \iff \alpha < \frac{a-\theta}{2} \tag{23}$$

Consider the case when k^o and k^a are high enough. Thus, when the marginal damage of pollution is sufficiently low, the tax is negative meaning that each regulator actually subsidizes pollution (or production because they are proportional) to deal with the monopoly distortion.

From (18) and (19), we have:

$$\lim_{k^o, k^a \to +\infty} k^o \hat{x}_i^o = \frac{\alpha (a - \theta - \alpha) + (a - \theta - 2\alpha) \gamma\beta}{2b} \tag{24}$$

and

$$\lim_{k^o, k^a \to +\infty} k^a \hat{x}_i^a = 0 \tag{25}$$

By using (24) and (25) in (21) and (22), we get:

$$\lim_{k^o,k^a\to+\infty} r^{of} = \frac{(a-\theta-\alpha)^2 + (a-\theta-2\alpha)\,\gamma\beta}{b} > \lim_{k^o,k^a\to+\infty} r^{af} = 0 \qquad (26)$$

For this we state the following proposition,

Proposition 5 *If $a > \theta + 2\alpha$, then when the investment-cost parameters are sufficiently high, the per-unit R&D subsidy for inventive research is higher than the one for absorptive research.*

Notice that condition (13) is satisfied and k^o and k^a are high enough, then when $a > \theta + 2\alpha$ the subsidy for original research is strictly positive. The investment in absorptive research is socially desired. This result is similar to a finding of Ben Youssef (2010).

3 International trade

In this section, it is assumed that when markets are opened to international trade, the inverse demand fonction is $p = a - \frac{b}{2}(q_i + q_j)$.

The firms profits are $\pi_i^c = p(q_i, q_j)\,q_i - \theta q_i - k^o(x_i^o)^2 - k^a(x_i^a)^2$ and their net profits are$V_i^c = \pi_i^c - t_i^c E_i + r_i^{oc} x_i^o + r_i^{ac} x_i^a$, with t_i^c is the emission tax per-unit of pollution, r_i^{oc} is the subsidy per-unit of original R&D level and r_i^{ac} is the subsidy per-unit of absorptive R&D level.

As in autarky, we make the following conjecture

Conjecture 6 $\lim_{k^o,k^a\to+\infty} x_i^{oc} = \lim_{k^o,k^a\to+\infty} x_i^{ac} = 0$

The total consumer surplus is equally divided between the two symmetric countries :

$$CS_i^f = \int_0^{q_i+q_j} p(u)\,du - p(q_i, q_j)(q_i, q_j) = \frac{b}{8}(q_i + q_j)^2$$

And the social welfare of country i is

$$S_i^c\left(q_i, q_j, x_i^o, x_i^a, x_j^o, x_j^a\right) = CS_i^c - D_i + \pi_i^c \tag{27}$$

3.1 The reaction of firms

By backward induction, at the third stage each firm maximizes its net profit with respct to its production level and at second stage, it maximizes its net profit with respect to its R&D levels.

The first-order conditions of the firms third stage are:

$$\frac{\partial V_i^c}{\partial q_i} = \frac{\partial V_j^c}{\partial q_j} = 0 \tag{28}$$

The resolution of system (28) gives:

$$q_i^{*c} = \frac{2\left[a - \theta + t_j\left(1 - x_j^o - \left[\beta + l x_j^a\right] x_i^o\right) - 2t_i\left(1 - x_i^o - \left[\beta + l x_i^a\right] x_j^o\right)\right]}{3b} \tag{29}$$

The partiel derivations set for the symmetric case are:

$$\frac{\partial q_i^{*c}}{\partial x_i^o}=\frac{2t_i}{3b}\left(2-\left[\beta+lx_i^a\right]\right);\frac{\partial q_i^{*c}}{\partial x_i^a}=\frac{4lx_i^o}{3b}t_i$$
$$\frac{\partial q_i^{*c}}{\partial x_j^o}=\frac{2t_i}{3b}\left(2\left[\beta+lx_i^a\right]-1\right);\frac{\partial q_i^{*c}}{\partial x_j^a}=-\frac{2lx_i^o}{3b}t_i$$

Consider the case of a positive emission tax. When a firm increase its level of original or a absorptive research, its emissions/output ratio decrease enabling it to expand its production. When the competing firm increase its original research, this has tow opposite effects on the production of the firm: because of R&D spillovers and absorptive capacity, the emission ratio of firm decrease enabling it to expend its production; the second effect is a negative one and obliges the firm to decrease its production because the competing one can increase its production due to the decrease of its emission/output ratio.When β and/or l are high enough, the first positive effect dominates. When the competing firm increase its absorptive capacity, its emissions ratio decrease enabling it to expend its production which forces the firm to reduce its production.

The symmetric expression of (29) is:

$$q_i^{*c}=\frac{2\left[a-\theta-t_i\left(1-\left(1+\beta+lx_i^a\right)x_i^o\right)\right]}{3b} \tag{30}$$

The first-order conditions of the firm's second stage are:

$$\frac{dV_i^c}{dx_i^o}=\frac{\partial q_i^{*c}}{\partial x_i^o}\frac{\partial V_i^c}{\partial q_i}+\frac{\partial q_j^{*c}}{\partial x_i^o}\frac{\partial V_i^c}{\partial q_j}+\frac{\partial V_i^c}{\partial x_i^o}=0 \tag{31}$$

and

$$\frac{dV_i^c}{dx_i^a} = \frac{\partial q_i^{*c}}{\partial x_i^a}\frac{\partial V_i^c}{\partial q_i} + \frac{\partial q_j^{*c}}{\partial x_i^a}\frac{\partial V_i^c}{\partial q_j} + \frac{\partial V_i^c}{\partial x_i^a} = 0 \tag{32}$$

At the equilibrium, by using (28), (31)-(32) are simplified, and the following equations are satisfied for symmetric solutions:

$$\frac{2}{3}\left(2 - \beta - lx_i^a\right) t_i^c q_i^{*c} + r_i^{oc} - 2k^o x_i^{oc} = 0 \tag{33}$$

and

$$\frac{4}{3} t_i^c l x_i^o q_i^{*c} + r_i^{ac} - 2k^a x_i^{ac} = 0 \tag{34}$$

where q_i^{*c} is given by (30). This system contains two equations and two unknown variables which are x_i^{oc} and x_i^{ac}.

3.2 The Optimal per-unit Emission Tax and R&D Subsidies

Given that the socially optimal per-unit emission-tax and per unit R&D subsidies are reached in the first stage, regulators determine the socially optimal production and R&D levels in the third and second stages, respectively. Then, by equalizing the socially optimal quantities obtained to those chosen by the taxed and subsidized firm, they determine the socially optimal per-unit emission tax and per-unit R&D subsidies.

The first-order conditions of the regulators third stage are:

$$\frac{\partial S_i^c}{\partial q_i} = \frac{\partial S_j^c}{\partial q_j} = 0 \tag{35}$$

The resolution of this system gives:

$$\hat{q}_i^c = \frac{\left[2\left(a-\theta-\alpha\right)+\alpha x_i^o\left(3-\left(\beta+lx_j^a\right)\right)+\alpha x_j^o\left(3(\beta+lx_i^a)-1\right)\right]}{2b} \tag{36}$$

The transboundary pollution is completely not internalized because the above quantity does not depend on the marginal damage of the foreign pollution (γ).

The symmetric production quantities are given by (36) is:

$$\hat{q}_i^c = \frac{\left[a-\theta-\alpha+(1+\beta+lx_i^a)\alpha x_i^o\right]}{b} \tag{37}$$

In order that the socially optimal production quantities must be positive we found the same condition in the autarky regime. This condition is as follows.

$$a > \theta+\alpha \iff a-\theta > \alpha \tag{38}$$

The first-order conditions of regulator's second stage are

$$\frac{dS_i^c}{dx_i^o} = \frac{\partial \hat{q}_i^c}{\partial x_i^o}\frac{\partial S_i^c}{\partial q_i} + \frac{\partial \hat{q}_j^c}{\partial x_i^o}\frac{\partial S_i^c}{\partial q_j} + \frac{\partial S_i^c}{\partial x_i^o} = 0 \tag{39}$$

and

$$\frac{dS_i^c}{dx_i^a} = \frac{\partial \hat{q}_i^c}{\partial x_i^a}\frac{\partial S_i^c}{\partial q_i} + \frac{\partial \hat{q}_i^c}{\partial x_i^a}\frac{\partial S_i^c}{\partial q_j} + \frac{\partial S_i^c}{\partial x_i^a} = 0 \tag{40}$$

At the equilibrium, equations (39)-(40) are simplified by using (35), and the symmetric solutions verify the following equations system:

$$2b\left[\alpha+\gamma\left(\beta+lx_i^{ac}\right)\right]\hat{q}_i^c-\alpha\gamma\left[3\left(\beta+lx_i^{ac}\right)-1\right] \qquad (41)$$
$$\times\left[1-\left(1+\beta+lx_i^{ac}\right)x_\iota^{oc}\right]-4bk^o x_i^{oc}=0$$

and

$$2b\alpha l x_i^{oc}\hat{q}_i^c+\alpha\gamma l\left[1-\left(1+\beta+lx_i^{ac}\right)x_\iota^{oc}\right]x_\iota^{oc}-4bk^a x_i^{ac}=0 \qquad (42)$$

where $\hat{q}_i^c$ is given by (37), the system (41)-(42) are equivalent to:

$$2\left(a-\theta\right)\left[\alpha+\gamma\left(\beta+lx_i^{ac}\right)\right]-\alpha\left[1-\left(1+\beta+lx_i^{ac}\right)x_\iota^{oc}\right] \qquad (43)$$
$$\times\left[2\alpha+5\gamma\left(\beta+lx_i^{ac}\right)-\gamma\right]-4bk^o x_i^{oc}=0$$

and

$$\alpha l x_i^{oc}\left[2\left(a-\theta\right)+\left(1-\left(1+\beta+lx_i^{ac}\right)x_i^{oc}\right)\left(\gamma-2\alpha\right)\right]-4bk^a x_i^{ac}=0 \qquad (44)$$

From this system, we can state the following proposition.

Proposition 7 *In addition, the competition of firms on the commun market enable non-cooperating countries to better internalize transboundary pollution. The higher β and/or the ability to absorb is, the greater is the proportion of transboundary pollution internalized.*

As in autarky, the resolution of the non-linear equations system (43)-(44) gives two equations with two unknown variables which are the symmetric socially optimal R&D levels denoted by $\hat{x}_i^{oc}$ and $\hat{x}_i^{ac}$. Moreover, we are not able to find the explicit solutions. Indeed, we have the followind proposition

Proposition 8 *When k^o and k^a are sufficiently high, there are at least one and at most five couples of real solutions $\hat{x}_i^{oc} > 0$ and $\hat{x}_i^{ac} > 0$ that solve the non-linear equations system given by* (43) *and* (44)*.*

PROOF. See the appendix.

By equalizing the production level chosen by firms, we determine the socially optimal emission tax:

$$t_i^c = \frac{2\,(a-\theta) - 3b\hat{q}_i^c}{2\,[1-(1+\beta+lx_i^{ac})x_i^{oc}]} \tag{45}$$

And Equations (33), and (34) give the socially optimal R&D subsidies:

$$r_i^{oc} = 2k^o x_i^o - \frac{2}{3}\,(2-\beta-lx_i^a)\,t_i^c\hat{q}_i^c \tag{46}$$

and

$$r_i^{ac} = 2k^a x_i^a - \frac{4}{3}t_i^c l x_i^o \hat{q}_i^c \tag{47}$$

Thus, we can establish the following proposition.

Proposition 9 *When there is a common market, by using the three regulatory instruments, which are a per-unit emission tax, a per-unit original research subsidy, and a per-unit absorptive research subsidy, regulators can push their* *firms to implement the noncooperative socially optimal levels of production and R&D.*

By using the conjecture, (45) and (46), we obtain:

$$\lim_{k^o,k^a\to+\infty} t_i^c = \frac{3\alpha-(a-\theta)}{2} < 0 \iff \alpha < \frac{a-\theta}{3} \tag{48}$$

Therfore, when the marginal damage of pollution is high enough, the regulator taxes pollution (or production) and when its low enough, he subsidizes production to deal with the monopoly distortion.

Further, from (43) and (44), we have:

$$\lim_{k^o,k^a\to+\infty} k^o x_i^{oc} = \frac{2\alpha\left(a-\theta-\alpha\right)+\gamma\beta\left(2a-2\theta-5\alpha\right)+\alpha\gamma}{4b} \tag{49}$$

and

$$\lim_{k^o,k^a\to+\infty} k^a x_i^{ac} = 0 \tag{50}$$

By using (50) and (49) in (47) and (46), we get:

$$\lim_{k^o,k^a\to+\infty} r^{oc} = \frac{2(a-\theta-\alpha)[3\alpha(\beta-1)+(2-\beta)(a-\theta)]+3\gamma[2\beta(a-\theta-\alpha)+\alpha(1-3\beta)]}{2b} \tag{51}$$

$$\lim_{k^o,k^a\to+\infty} r^{ac} = 0 \tag{52}$$

The following proposition compares the subsidy rates of efforts in original and absorptive R&D, when markets are opened to international trade.

Proposition 10 *When markets are opened to international trade, and when the investment-cost parameters are sufficiently high, the per-unit R&D subsidy for inventive research is higher than the one for absorptive research, when* $\beta < \frac{1}{3}$.

This proposition imply that when k^o and k^a are high enough. Thus, when the marginal damage of pollution is sufficiently low, the subsidy for original research is always positive.

4 Common market versus autarky

In either case we have studied each regulator chooses the socially optimal production and R&D levels and, by means of the per-unit emission tax, a per-unit original research subsidy, and a per-unit absorptive research subsidy, puches his firm to implement them for the two market regimes. For this, we compare the taxes and subsidies also that the original research of the both cases.

Subsequently, to simplify our computations, we will replace the marginal damage of the domestic pollution by the marginal damage of the foreign pollution, ie $\alpha = \gamma$.

Proposition 11 *When the markets are opened to international trade, and when the investment-cost parameters are sufficiently high, the original research increases.*

PROOF. See the appendix.

The better internalization of transboundary pollution generated by competition in the common market is realised by an increase of the level of the original research when the investment-cost parameters are sufficiently high. Consequently, the absorptive research increase and the emission ratio is lower, which encourages firms to produce more in common market.

Proposition 12 *The per-unit emission tax and the per-unit R&D subsidy for inventive research are greater in common market than in autarky, when the investment-cost parameters are sufficiently high.*

PROOF. See the appendix.

Opening markets to international trade and investment in absorptive research better internalize transboundary pollution and this procure by an increase of the emission tax and of the R&D subsidy for inventive research. This result differs from that of Ben Youssef (2009) where he has shown that the emission tax is higher but the R&D subsidy is lower when α is low enough.

We note that if there is no negative externality between countries, so many optimal values in autarky and commun market become equal. In fact, if $\gamma = 0$, equations system (18)-(19) and (43)-(44) and show that the R&D levels are equal which implies that production, pollution, and social welfare are equal in the two market regimes.

5 Conclusion

We have developed a non-cooperative three-stage game model composed by two regulator-firm hierarchies in presence of transborder pollution, the R&D spillovers and the absorptive capacity. We study the effects of the positive R&D externality, the ability to capture part of original research developed from other firms and international trade on the internaliszation of the transboundary polllution. Firms have the possibility to invest in original and in absorptive research to reduce their emission/output ratio. Indeed, we evaluate the impact of international competition on the original research, by means the emission-tax and the R&D subsidies.

We show that free R&D spillovers, the investment in absorptive research and the common markets enable non-cooperating countries to better internalize transboundary pollution. The higher the learning parameter of absorptive capacity and the R&D spillovers are, the higher the proportion of transboundary pollution internalized is.

Interestingly, for autarky and international trade cases the learning ability of firms may lead to multiple subgame perfect Nash equilibria necessitating non-cooperating countries to coordinate on an equilibrium, which constitutes an incentive for them to cooperate. Accordingly, transboundary pollution will be completely internalized and the first best outcome may be reached.

Opening markets to international trade helps competing countries to better internalize transboundary pollution through the competition firms on the common market. Consequently, the per-unit emission tax and the per-unit subsidy for inventive research increase with market opened for international trade.

6 Appendix

A) In autarky case, the second-order conditions of the firms second stage consider the Hessian matrix:

$$H_V = \begin{pmatrix} \frac{d^2V_i^f}{dx_i^{o2}} & \frac{d^2V_i^f}{dx_i^o x_i^a} \\ \\ \frac{d^2V_i^f}{dx_i^o x_i^a} & \frac{d^2V_i^f}{dx_i^{a2}} \end{pmatrix}$$

By using the first-order conditions given by (5) and (6), we can determine the second derivatives consiting matrix H_{V^f} which can be written as:

$$H_V = \begin{pmatrix} g_1 - 2k^o & g_2 \\ \\ g_2 & g_3 - 2k^a \end{pmatrix}$$

where $g_{i,i=1,2,3}$ are polynomial functions in t_i^f and x_i^{of} (symmetric case).

Since $\lim\limits_{k^o,k^a \to +\infty} x_i^{of}$ and $\lim\limits_{k^o,k^a \to +\infty} t_i^f$ are finite numbers, then g_i take finite values when k^o and k^a tend to $+\infty$.

Therefore, when k^o and k^a are sufficiently high:

a.$\frac{d^2V_i^f}{dx_i^{o2}} < 0$ and $\frac{d^2V_i^f}{dx_i^{a2}} < 0$

b.$\det H_V = (g_1 - 2k^o)(g_3 - 2k^a) - g_2^2 > 0$.

Thus, we have a maximum when k^o and k^a are high enough.

B) Second-order conditions of the regulators seconds stage, in autarky case, consider the Hessian matrix:

$$H_S = \begin{pmatrix} \frac{d^2 S_i^f}{dx_i^{o2}} & \frac{d^2 S_i^f}{dx_i^o x_i^a} \\ \\ \frac{d^2 S_i^f}{dx_i^o x_i^a} & \frac{d^2 S_i^f}{dx_i^{a2}} \end{pmatrix}$$

By using the first-order conditions given by (14) and (15), we can determine the second derivatives consiting matrix H_{S^f} which can be written as:

$$H_S = \begin{pmatrix} f_1 - 2k^o & f_2 \\ \\ f_2 & f_3 - 2k^a \end{pmatrix}$$

where $f_{i,i=1,2,3}$ are polynomial functions in t_i^f and x_i^{of} (symmetric case).

Since $\lim_{k^o,k^a \to +\infty} x_i^{of} = \lim_{k^o,k^a \to +\infty} x_i^{af} = 0$, then f_i take finite values when k^o and k^a tend to $+\infty$.

Therefore, when k^o and k^a are sufficiently high:

a.$\frac{d^2 S_i^f}{dx_i^{o2}} < 0$ and $\frac{d^2 S_i^f}{dx_i^{a2}} < 0$

b.det $H_S = (f_1 - 2k^o)(f_3 - 2k^a) - f_2^2 > 0$.

Thus, we have a maximum when k^o and k^a are high enough.

C) Proof of proposition 3

From , we deduce:

$$x_i^{af} = \frac{\alpha l \left[a - \theta - \alpha + \alpha (1+\beta) x_\iota^{of}\right] x_\iota^{of}}{2bk^a - \alpha^2 l^2 x_\iota^{of2}} \tag{53}$$

Expression (18) is equivalent to:

$$\begin{gathered}\alpha\left(a-\theta-\alpha\right)+\gamma\beta\left(a-\theta-2\alpha\right)+\gamma l\left(a-\theta-2\alpha\right)x_i^{af} \\ +\left[\left(1+\beta\right)\left(\alpha+2\gamma\beta\right)\alpha-2bk^o\right]x_\iota^{of}+\left[\alpha+2\gamma\left(2\beta+1\right)\right]\alpha l x_i^{af}x_\iota^{of} \\ +2l^2\alpha\gamma x_i^{af2}x_\iota^{of}=0\end{gathered} \tag{54}$$

by using (53) in (54), and then multiplying by $\left(2bk^a-\alpha^2l^2x_\iota^{of2}\right)^2$, we get a polynomial function of degree 5 in x_ι^{of}; $A\left(x_\iota^{of}\right)=0$. The constant term of A is $4b^2\left[\alpha\left(a-\theta-\alpha\right)+\gamma\beta\left(a-\theta-2\alpha\right)\right]k^{a2}>0$ and the coefficient of $\left(x_\iota^{of}\right)^5$ is $-2bk^o\alpha^4l^4<0$.

We have $A\left(0\right)>0$ and $\lim\limits_{k^o,k^a\to+\infty}A\left(x_i^{of}\right)=-\infty$, then $A\left(x_\iota^{of}\right)$ admits at least one and at most five real and positive roots $\hat{x}_i^{of}$. Since $\hat{x}_i^{of}>0$, from expression (54) and condition (13), we have $\hat{x}_i^{af}>0$ when k^o and k^a are high enough.

D) Second-order conditions of the firms second stage in trade international case consider the Hessian matrix:

$$H_V=\begin{pmatrix}\frac{d^2V_i^c}{dx_i^{o2}} & \frac{d^2V_i^c}{dx_i^o x_i^a} \\ \\ \frac{d^2V_i^c}{dx_i^o x_i^a} & \frac{d^2V_i^c}{dx_i^{a2}}\end{pmatrix}$$

By using the first-order conditions given by (31) and (32), we can determine the second derivatives consiting matrix H_V which can be written as:

$$H_V=\begin{pmatrix}g_1^c-2k^o & g_2^c \\ \\ g_2^c & g_3^c-2k^a\end{pmatrix}$$

where $g_{i,i=1,2,3}^c$ are polynomial functions in t_i^f and x_i^{of} (symmetric case).

Since $\lim\limits_{k^o,k^a\to+\infty} x_i^{oc}$ and $\lim\limits_{k^o,k^a\to+\infty} t_i^c$ are finite numbers, then g_i^c take finite values when k^o and k^a tend to $+\infty$.

Therefore, when k^o and k^a are sufficiently high:

a.$\frac{d^2V_i^c}{dx_i^{o2}} < 0$ and $\frac{d^2V_i^c}{dx_i^{a2}} < 0$

b.$\det H_V = (g_1^c - 2k^o)(g_3^c - 2k^a) - g_2^2 > 0.$

Thus, we have a maximum when k^o and k^a are high enough.

E) Second-order conditions of the regulators seconds stage consider in trade international case the Hessian matrix:

$$H_S = \begin{pmatrix} \frac{d^2S_i^c}{dx_i^{o2}} & \frac{d^2S_i^c}{dx_i^o x_i^a} \\ \\ \frac{d^2S_i^c}{dx_i^o x_i^a} & \frac{d^2S_i^c}{dx_i^{a2}} \end{pmatrix}$$

By using the first-order conditions given by (39) and (40), we can determine the second derivatives consiting matrix H_S which can be written as:

$$H_S = \begin{pmatrix} f_1 - 2k^o & f_2 \\ \\ f_2 & f_3 - 2k^a \end{pmatrix}$$

where $f_{i,i=1,2,3}$ are polynomial functions in x_i^{ac} and x_i^{oc} (symmetric case).

Since $\lim\limits_{k^o,k^a\to+\infty} x_i^{oc} = \lim\limits_{k^o,k^a\to+\infty} x_i^{ac} = 0$, then f_i take finite values when k^o and k^a tend to $+\infty$.

Therefore, when k^o and k^a are sufficiently high:

a.$\frac{d^2S_i^c}{dx_i^{o2}} < 0$ and $\frac{d^2S_i^c}{dx_i^{a2}} < 0$

b.det $H_S = (f_1 - 2k^o)(f_3 - 2k^a) - f_2^2 > 0.$

Thus, we have a maximum when k^o and k^a are high enough.

F) Proof of the proposition 8

From (44), we deduce:

$$x_i^{ac} = \frac{\alpha l \left[2(a-\theta) + (\gamma - 2\alpha)\left(1 - (1+\beta) x_i^{oc}\right)\right] x_\iota^{oc}}{4bk^a + \alpha l^2 (\gamma - 2\alpha) x_\iota^{oc2}} \tag{55}$$

Expression (43) is equivalent to:

$$\begin{gathered}\alpha(2a - 2\theta - 2\alpha - \gamma) + \gamma\beta(2a - 2\theta - 5\alpha) \\ +\gamma l(2a - 2\theta - 5\alpha) x_i^{ac} + \left[\alpha(1+\beta)(2\alpha + 5\gamma\beta - \gamma) - 4bk^o\right] x_\iota^{oc} \\ +2\alpha(\alpha + 5\gamma\beta - 2\gamma) l x_i^{ac} x_\iota^{oc} + 5l^2 \alpha\gamma x_i^{ac2} x_\iota^{oc} = 0\end{gathered} \tag{56}$$

by using (55) in (56), and then multiplying by $\left[4bk^a + \alpha l^2(\gamma - 2\alpha) x_\iota^{oc2}\right]^2$, we get a polynomial function of degree 5 in x_ι^{oc}; $B(x_\iota^{oc}) = 0$.The constant term of B is $8b^2\left[\alpha(2a - 2\theta - 2\alpha - \gamma) + \gamma\beta(2a - 2\theta - 5\alpha)\right] k^{a2} > 0$ and the coefficient of $(x^{oc})^5$ is $-4(\gamma - 2\alpha) bk^o \alpha^2 l^4 < 0$.

We have $B(0) > 0$ and $\lim\limits_{k^o, k^a \to +\infty} B(x_i^{oc}) = -\infty$, then $B(x_\iota^{oc})$ admits at least one and at most five real and positive roots $\hat{x}_i^{oc} > 0$. Since $\hat{x}_i^{oc} > 0$, from expression (56) and condition of $a > \theta + \alpha \iff a - \theta > \alpha$, we have $\hat{x}_i^{ac} > 0$ when k^o and k^a are high enough.

G) Proof of proposition 10

To compare the $\lim\limits_{k^o,k^a\to+\infty} r^{oc}$ et $\lim\limits_{k^o,k^a\to+\infty} r^{ac}$, we assume that $\alpha = \gamma$ and we used the condition of $a > \theta + \alpha \iff (2-\beta)(a-\theta) > \alpha(2-\beta)$

$\iff 3\alpha(\beta-1) + (2-\beta)(a-\theta) > \alpha(2-\beta) + 3\alpha(\beta-1)$, thus, we have $2(a-\theta-\alpha)[3\alpha(\beta-1)+(2-\beta)(a-\theta)] + 6\alpha\beta(a-\theta) + 3\alpha^2(1-5\beta) > \alpha\left[2(a-\theta)(5\beta-1) + \alpha(5-19\beta)\right]$

And after all calculation is obtained

$2(a-\theta-\alpha)[3\alpha(\beta-1)+(2-\beta)(a-\theta)]+6\alpha\beta(a-\theta)+3\alpha^2(1-5\beta) > 3\alpha^2(1-3\beta)$. Indeed, if $3\alpha^2(1-3\beta)$ is positif then $\beta < \frac{1}{3}$.

H) Proof of proposition 11

From (24) and (49) , we have $\lim\limits_{k^o,k^a\to+\infty} k^o x_i^{oc} - \lim\limits_{k^o,k^a\to+\infty} k^o x_i^{of} = \dfrac{\alpha\gamma(1-\beta)}{4b} > 0$ because $(1-\beta) > 0$. Since k^o and k^a are high enough, then $x_i^{oc} > x_i^{of}$, this imply that $e_i^c < e_i^f$ and we also have $\hat{q}_i^c > \hat{q}_i^f$.

I) Proof of proposition 12

From (23) and (48), and the condition of $a > \theta + \alpha \iff a - \theta > \alpha$, we have

$\lim\limits_{k^o,k^a\to+\infty} t_i^c - \lim\limits_{k^o,k^a\to+\infty} t_i^f = \dfrac{(a-\theta-\alpha)}{2} < 0$. Since k^o and k^a are high enough, then $t_i^c > t_i^f$.

And from (24) and (49), and by using the condition (38), we have

$$\lim_{k^o,k^a\to+\infty} r_i^{oc} - \lim_{k^o,k^a\to+\infty} r_i^{of} = \frac{2(a-\theta-\alpha)[3\alpha\beta-(a-\theta)(1+\beta)]-3\alpha^2(\beta-1)}{6b} > 0.$$

Since k^o and k^a are high enough and when the marginal damage of pollution is sufficiently low , then $r_i^{oc} > r_i^{of}$.

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