Absorptive Capacity, RD Spillovers, Emissions Taxes and RD Subsidies

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Abstract

In this paper, we consider a duopoly competing in quantity, where firms can invest in R&D to control their emissions. We distinguish between efforts carried out to acquire first-hand knowledge (inventive R&D) and efforts made to develop an absorptive capacity to be able to capture part of the knowledge developed by the rival. There are also free R&D spillovers between firms. We show that a regulator can reach the first best by using three regulatory instruments, which are a per-unit emissions tax, a per-unit inventive-research subsidy and a per-unit absorptive-research subsidy. The socially optimal R&D level for inventive research is higher than the one for absorptive capacity, even when the investment-cost parameters for inventive and absorptive research are equal and when there is both very little free spillover and a very high learning parameter. Interestingly, when the free spillover is high enough, the regulator gives a greater per-unit subsidy to inventive research, and when it is low enough and the marginal damage cost of pollution is sufficiently high, he supports absorptive research to strengthen R&D spillovers. Moreover, inventive research is actually taxed when the free spillover is low and the marginal damage cost of pollution is high.

Key Words: Pollution Control; Inventive R&D; Absorptive Capacity; Taxes and Subsidies; First Best.

1 Introduction

It is widely recognized that (i) the development and diffusion of cleaner technologies play an important role in achieving environmental-quality goals; (ii) firms benefit from each other's investments in research and development (R&D) through voluntary (e.g., joint ventures) and/or involuntary spillovers; and (iii) regulators can influence firms' R&D efforts toward emissions reduction through economic incentives (e.g., taxes and subsidies). The aim of this paper is to characterize the socially optimal production (or emissions) levels, investment in inventive R&D (IR&D) and in absorptive R&D (AR&D), and tax and subsidy rates in a game played by two polluting duopolists and a regulator.

One of the early studies in the environmental R&D area is Milliman and Prince (1989). The authors considered a competitive industry formed of identical firms and evaluated the relative merits of different environmental-policy instruments for promoting technological change in pollution control, namely, direct controls, emissions subsidies, emissions taxes, free marketable permits, and auctioned marketable permits. They showed that emissions taxes and auctioned permits provide the highest firm incentives to promote technological change. Jung, Krutilla and Boyd (1996) extended this comparative approach to a heterogeneous industry. Dosi and Moretto (1997) studied the regulation of a firm that can switch to a green technology by incurring an irreversible investment cost. This technological switch is expected to provide benefits, but, however, is surrounded by a certain degree of uncertainty. To bridge the gap between the firm's and the policy-maker's desired timing of innovation, they recommended that the regulator should stimulate the innovation through subsidies and by reducing the uncertainty surrounding the profitability of the new technology through appropriate announcements. Farzin and Kort (2000) studied the regulation of a competitive firm and examined the effect of a higher pollution-tax rate on abatement investment, both under full certainty and when the timing or the size of the tax increase is uncertain. They showed the possibility that a higher pollution-tax rate induces more pollution and that a credible threat to the acceleration of tax increase can lead to more abatement investment. Requate and Unold (2003) investigated incentives given by environmental-policy instruments to get firms to adopt advanced abatement technology. Fischer and Newell (2008) assessed different policies for reducing carbon-dioxide emissions and encouraging innovation and diffusion of renewable energy. They evaluated the relative performance of policies according to the incentives provided for emissions reduction, efficiency, and other outcomes. They also assessed how the nature of technological progress through learning and R&D, and the degree of knowledge spillovers, affected the desirability of different policies. Because of knowledge spillovers, the optimal policy involves a portfolio of different instruments targeted at emissions, learning, and R&D. Ben Youssef (2009) considered a non-cooperative and symmetric three-stage game played by two regulator-firm hierarchies. He showed that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transboundary pollution. Surprisingly, international competition increases the per-unit emissions tax and decreases the per-unit R&D subsidy.

In the above literature, the assumption is either that there are no technological spillovers between the firms, or that when they occur, they are free. As pointed out in many papers in the industrial-organization literature, this assumption may be strong in the sense that firms need to acquire an absorptive capacity to assimilate and exploit the available information, to benefit from these technological spillovers.

Cohen and Levinthal (1989) were the first to introduce the idea of absorptive capacity in the (process or cost reduction) R&D literature. Contrary to the result achieved in the seminal paper by D'Aspremont and Jacquemin (1988,1990) and the one by Kamien, Muller and Zang (1992), were R&D spillovers are assumed exogenous and cost-free, Cohen and Levinthal showed that the investment in R&D develops the firm's ability to identify, assimilate and exploit knowledge from the environment. Kamien and Zang (2000) modeled a firm's "effective" R&D level, which reflects how both its R&D approach (firm-specific or general) and R&D level influence its "absorptive capacity". They found that, when firms cooperate in R&D, they choose identical R&D approaches. When they do not form a research joint venture (RJV), they choose firm-specific R&D approaches, unless there is no danger of exogenous spillovers. In contrast to the finding in Kamien and Zang, Wiethaus (2005) showed that competing firms choose identical R&D approaches in order to maximize the flow of knowledge between them. Leahy and Neary (2007) specified a general model for the absorptive-capacity process and showed that costly absorption raises the effectiveness of own R&D and lowers the effective spillover coefficient, thereby weakening the case for encouraging RJVs even if there is total information-sharing between firms. Hammerschmidt (2009) distinguished between two types of R&D: inventive (or original) R&D that creates new knowledge and absorptive R&D that enables a firm to benefit from the inventive research conducted by others. She showed that firms invest more in R&D to strengthen their absorptive capacity when the spillover parameter is higher.

We consider a three-stage game consisting of a regulator and two identical firms competing in quantity and producing the same homogeneous good. The production process generates pollution and firms can invest in R&D to lower their emissions/output ratio. Firms invest in IR&D that directly reduces their emissions/output ratios. They also invest in AR&D, which enables a firm to exploit the original research done by others. There are also free R&D spillovers between firms. Since firms constitute a duopoly and pollute the environment, they are regulated. In the first stage, the regulator announces a tax per-unit of pollution to induce the socially optimal level of pollution and production, a subsidy per-unit of original research to induce the socially optimal level of IR&D, and a subsidy per unit of absorptive-capacity research to induce the socially optimal level of AR&D. In the second stage, firms invest in R&D, and in the third one they compete in quantity on the product market.

To the best of our knowledge, this paper is the first attempt to integrate into the same model costly R&D spillovers and pollution control. We add costly R&D spillovers to the environmental concern because the problem then better conforms to real world regulatory policies as showed by the rich industrial organization literature dealing with absorptive capacity.

Our main results are as follows:

1. Using the three instruments, namely, the per-unit emissions tax, the per-unit IR&D subsidy, and the per-unit AR&D subsidy, the regulator can induce competing firms to implement the socially optimal levels of production and research. These three instruments are necessary to our model. Indeed, even if the socially optimal level of pollution can be implemented through only one instrument, such as pollution permits, this does not provide an incentive for the firms to implement the socially optimal levels of production and R&D.

2. Interestingly, the socially optimal level of IR&D is higher than the one for AR&D even when the investment-cost parameters for IR&D and AR&D are equal, the free spillover is zero, and the learning parameter is very high. This result contradicts the simulation results in Hammerschmidt (2009) where it is found that firms invest more in AR&D when the spillover parameter is higher.

3. When the free spillover is sufficiently high, the regulator gives a higher per-unit subsidy for original research; however, and interestingly, when it is low enough and the marginal damage cost of pollution is sufficiently high, he gives a higher per-unit subsidy for absorptive research to strengthen R&D spillovers. This result contradicts the finding of Jin and Troege (2006) who showed that, for the society and consumers, the marginal value of innovation expenditure is always higher than that of imitation.

4. When the free spillover is low and the marginal damage cost of pollution is high, the regulator really taxes IR&D. This constitutes an interesting result from the environmental point of view since it holds only when the environmental concern is important.

The paper has the following structure. Section 2 presents the model and Section 3 studies the reaction of firms to the regulator's policy. In Section 4, we derive the socially optimal regulatory instruments and we make some comparisons between innovation and absorption. Section 5 concludes and an Appendix contains some proofs.

2 The model

We consider an industry made up of two firms producing a homogeneous good sold on a market having the following inverse demand function:

$$p(q_i, q_j) = a - (q_i + q_j), \quad a > 0.$$

What justifies the market structure we use is that the industries investing in R&D are often characterized by oligopolistic structure.

The production process generates pollution and firms can invest in abatement capacity to decrease their emissions per-unit of production. We suppose that this abatement capacity requires, and is positively related to, R&D activities. We distinguish between two types of R&D efforts, namely, original or inventive R&D, denoted x_i^o, and absorptive-capacity R&D, denoted x_i^a. To better visualize this, think of IR&D as activities related to, e.g., developing better air-filtering systems, whereas AR&D corresponds to efforts dedicated to improving the firm's technological-monitoring capacity through, e.g., hiring engineers and technicians and buying information technology (IT) equipment. The total knowledge available (also referred to as the effective R&D level in the literature) to firm i is:

$$x_i = x_i^o + (\beta + l x_i^a)\, x_j^o, \tag{1}$$

where $\beta \in [0, 1)$ is a parameter capturing the free and exogenous R&D spillover and $l > 0$ is a learning or absorptive parameter. Since a firm cannot get as research externality more than the original research developed by the competing one, we impose the constraint $0 \leq \beta + l x_i^a \leq 1$.

The above specification generalizes the one in D'Aspremont and Jacquemin (1988, 1990) by the addition of a new component of spillover that is not free and requires an investment in absorptive capacity. It differs from Jin and Troege (2006) and Hammerschmidt (2009), mainly by considering a component of free spillover which is independent of absorptive capacity.

Denote by $e_i\left(x_i^o, x_i^a, x_j^o\right)$ the emissions per-unit of production. It is assumed that $e_i\left(x_i^o, x_i^a, x_j^o\right)$ is decreasing in all its arguments. For simplicity, we adopt the following functional form:[1]

$$e_i(x_i^o, x_i^a, x_j^o) = 1 - x_i^o - (\beta + l x_i^a)\, x_j^o. \tag{2}$$

Consequently, the total emissions by firm i are given by

$$E_i(q_i, x_i^o, x_i^a, x_j^o) = \left[1 - x_i^o - (\beta + l x_i^a)\, x_j^o\right] q_i.$$

The damage cost resulting from these emissions is given by $D_i = \alpha E_i$, where $\alpha > 0$ is the marginal disutility of pollution.

We suppose that the cost of R&D activity of type $m = o, a$, given by $C^m\left(x_i^m\right)$, are given by increasing convex functions satisfying $C^m(0) = 0$. Hence, we have diminishing returns to scale of R&D. For tractability, we adopt the following quadratic functional forms:

$$C^m\left(x_i^m\right) = k^m \left(x_i^m\right)^2, \quad k^m > 0, \quad m = o, a,$$

[1] Actually, one first needs to translate the R&D effort into abatement. One easy way of doing this is to suppose that

$$e_i(x_i^o, x_i^a, x_j^o) = e_i^0 - f_i\left(x_i^o, x_i^a, x_j^o\right),$$

where e_i^0 corresponds to the emissions per-unit of production in the absence of any abatement effort, and $f_i\left(x_i^o, x_i^a, x_j^o\right)$ is a function transforming R&D effort into abatement. Our formulation assumes

$$e_i^0 = 1 \text{ and } f_i\left(x_i^o, x_i^a, x_j^o\right) = x_i^o + (\beta + l x_i^a)\, x_j^o.$$

and make the following conjecture:

$$\lim_{k^o,k^a \to +\infty} x_i^o = \lim_{k^o,k^a \to +\infty} x_i^a = 0. \tag{3}$$

This intuitive conjecture simply states that when the investment-cost parameters are relatively very high, it is optimal not to invest in R&D.

As firms constitute a polluting duopoly, they are regulated. The regulator maximizes a social-welfare function and uses three regulatory instruments, namely, an emissions tax per-unit of pollution t to induce the socially optimal levels of production and pollution, a subsidy per-unit of IR&D r^o and a subsidy per-unit of AR&D r^a to induce the socially optimal levels of effective R&D and emission/output ratio. Note that, as the game is symmetric, we confine our interest to symmetric equilibria.

Denoting the constant marginal cost of production of firms by $\theta > 0$, the profit of firm i is given by

$$\Pi_i(q_i, q_j, x_i^o, x_i^a) = p(q_i, q_j)q_i - \theta q_i - k^o \left(x_i^o\right)^2 - k^a \left(x_i^a\right)^2,$$

and its net profit by

$$V_i(q_i, q_j, x_i^o, x_i^a, x_j^o) = \Pi_i - tE_i + r^o x_i^o + r^a x_i^a.$$

The consumer surplus corresponding to the consumption of $Q = q_i + q_j$ is:

$$CS(q_i, q_j) = \int_0^{q_i+q_j} p(u)du - p(q_i, q_j)(q_i + q_j) = \frac{1}{2}(q_i + q_j)^2. \tag{4}$$

The social welfare is defined as the consumer surplus, minus damages and subsidies, plus taxes and net profits of the firms, and is equal, after simplification, to

$$S(q_i, q_j, x_i^o, x_i^a, x_j^o, x_j^a) = CS - D_i - D_j + \Pi_i + \Pi_j. \tag{5}$$

Notice that taxes and subsidies do not appear in the social welfare function because we suppose that raising public funds is not costly. Indeed, taxes deducted from the firms' profits are added to the consumer welfare, and subsidies added to the firms' profits are deducted from the consumer welfare.

3 The reaction of firms

The game has three stages. In the first stage, the regulator announces the socially optimal per-unit emissions tax and per-unit R&D subsidies, i.e., the triplet (t, r^o, r^a). In the second stage, the firms choose their levels of R&D, and, finally, in stage 3, the firms select their production levels. To determine a subgame-perfect Nash equilibrium, we solve the game backward.

In the third stage, the firms' first-order conditions are:

$$\frac{\partial V_i}{\partial q_i} = \frac{\partial V_j}{\partial q_j} = 0. \tag{6}$$

Solving the system (6) leads to

$$q_i^* = \frac{1}{3}\left[a - \theta - t\left(1 - \left[2 - \left(\beta + lx_j^a\right)\right]x_i^o + \left[1 - 2\left(\beta + lx_i^a\right)\right]x_j^o\right)\right]. \tag{7}$$

To interpret the above functions, we compute their partial derivatives and consider the case of a positive emissions tax. When a firm increases its level of original or absorptive research, its emissions/output ratio decreases (see (2)), enabling it to expand its production ($\frac{\partial q_i^*}{\partial x_i^o} = \frac{t}{3}[2 - (\beta + lx_j^a)] > 0$ and $\frac{\partial q_i^*}{\partial x_i^a} = \frac{2}{3}tlx_j^o > 0$). Consider now the derivative $\frac{\partial q_i^*}{\partial x_j^o} = \frac{t}{3}[2(\beta + lx_i^a) - 1]$. When the competing firm increases its original research x_j^o, then this has two opposite effects on the firm's production, namely, (i) a positive effect on production due to the free R&D spillovers and absorptive capacity; and (ii) a negative effect due to competition between firms. (Recall that this is a model à la Cournot where outputs are strategic substitutes.) When β and/or l are high enough, the first positive effect dominates. When a competitor increases its absorptive capacity, its emissions ratio decreases, enabling it to expand its production, which in turn forces the other firm to reduce its production ($\frac{\partial q_i^*}{\partial x_j^a} = -\frac{t}{3}lx_i^o < 0$).

The symmetric optimal level of production for each firm is obtained from expression (7):

$$q^* = \frac{1}{3}\left(a - \theta - t\left[1 - x^o - \left(\beta + lx^a\right)x^o\right]\right). \tag{8}$$

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

$$\frac{dV_i}{dx_i^o} = \frac{\partial q_i^*}{\partial x_i^o}\frac{\partial V_i}{\partial q_i} + \frac{\partial q_j^*}{\partial x_i^o}\frac{\partial V_i}{\partial q_j} + \frac{\partial V_i}{\partial x_i^o} = 0, \tag{9}$$

$$\frac{dV_i}{dx_i^a} = \frac{\partial q_i^*}{\partial x_i^a}\frac{\partial V_i}{\partial q_i} + \frac{\partial q_j^*}{\partial x_i^a}\frac{\partial V_i}{\partial q_j} + \frac{\partial V_i}{\partial x_i^a} = 0. \tag{10}$$

At equilibrium, by using (6), (9)-(10) are simplified, and the following equations are satisfied for symmetric solution(s):[3]

$$\frac{2}{3}t\left(2 - \beta - lx^a\right)q^* - 2k^o x^o + r^o = 0, \tag{11}$$

$$\frac{4}{3}tlx^o q^* - 2k^a x^a + r^a = 0, \tag{12}$$

[2] The second-order conditions are verified in the Appendix when k^o and k^a are high enough. It is important to realize that we do not consider the case $k^o, k^a \to +\infty$ in this paper. Nevertheless, we use these limits for comparisons that still remain valid when $k^o$and k^a are finite and sufficiently high numbers. For example, if

$$\lim_{k^o, k^a \to +\infty} f(k^o, k^a) > \lim_{k^o, k^a \to +\infty} g(k^o, k^a),$$

this implies that there are finite numbers, say K_o and K_a, such that for any $k^o > K_o$ and $k^a > K_a$, we have $f(k^o, k^a) > g(k^o, k^a)$.

[3] We look for symmetric equilibria because the model is symmetric and for tractability. 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.

where q^* is given by (8).

In the next section, we will show how a suitable choice of policy instruments by the regulator induces the firms to select the socially optimal production and R&D levels, which are at the same time the unique solution to the non-linear equations system (11)-(12).

4 The socially optimal regulatory instruments

In the first stage, the regulator maximizes his social welfare, given by (5), with respect to the decision variables t, r^o and r^a. Note that solving directly for the optimal per-unit emissions tax and per-unit R&D subsidies, is an extremely hard problem. Therefore, we propose an indirect (and much simpler) method in which the regulator maximizes, in the third and second stages respectively, his social welfare with respect to the output and the R&D levels which become the new choice variables. Then, by equalizing the socially optimal quantities to those selected by the firms, the regulator determines the socially optimal per-unit emissions tax and per-unit R&D subsidies. In fact, the model is solved as if it were a two-stage game.

Since the regulator will look for the symmetric socially optimal quantities, the social-welfare function given by (5) is written as $S(q, x^o, x^a)$. The first-order condition of the regulator's third stage is:

$$\frac{\partial S}{\partial q} = 0. \tag{13}$$

Solving the above equation gives the symmetric socially-optimal level of production for each firm:

$$\hat{q} = \frac{1}{2}\left[a - \theta - \alpha + \alpha\left(1 + \beta + lx^a\right)x^o\right]. \tag{14}$$

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

$$\alpha < a - \theta, \tag{15}$$

that is, the marginal damage cost of pollution is lower than the maximum willingness to pay for the good minus its marginal cost of production. We assume from now on that this condition is fulfilled.

The first-order conditions of the regulator's second stage are:[4]

$$\begin{aligned} \frac{dS}{dx^o} &= \frac{\partial \hat{q}}{\partial x^o}\frac{\partial S}{\partial q} + \frac{\partial S}{\partial x^o} = 0, && (16) \\ \frac{dS}{dx^a} &= \frac{\partial \hat{q}}{\partial x^a}\frac{\partial S}{\partial q} + \frac{\partial S}{\partial x^a} = 0. && (17) \end{aligned}$$

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

At equilibrium, by using condition (13), equations (16)-(17) are simplified, and their symmetric solution(s) verify the following equations system:

$$\begin{aligned} \alpha\left(1+\beta+lx^{a}\right)\hat{q}-2k^{o}x^{o} &= 0, & (18)\\ \alpha lx^{o}\hat{q}-2k^{a}x^{a} &= 0, & (19)\end{aligned}$$

where $\hat{q}$ is given by (14), and (18) and (19) are equivalent to

$$\begin{aligned} \alpha\left(1+\beta+lx^{a}\right)\left[a-\theta-\alpha+\ \alpha\left(1+\beta+lx^{a}\right)x^{o}\right]-4k^{o}x^{o} &= 0, & (20)\\ \alpha lx^{o}\left[a-\theta-\alpha+\ \alpha\left(1+\beta+lx^{a}\right)x^{o}\right]-4k^{a}x^{a} &= 0. & (21)\end{aligned}$$

Solving the non-linear system (20)-(21) gives the symmetric socially-optimal R&D levels denoted by $\hat{x}^{o}$ and $\hat{x}^{a}$. Unfortunately, we are not able to get an explicit solution. Nevertheless, we will prove the existence of a positive one.

Proposition 1 *When k^{o} and k^{a} are high enough, there are at least one and at most five couple of real solutions $\hat{x}^{o}>0$ and $\hat{x}^{a}>0$ that solve the non-linear equations system given by* (*20*) *and* (*21*)*; these symmetric solutions maximize the social-welfare function.*

Proof. See Appendix. ■

The above proposition shows the possibility of multiple symmetric equilibria maximizing the social-welfare level. The regulator have to select one of them.

Condition (15) and the assumption in (3) guarantee that the symmetric socially optimal levels of research, production and pollution are positive, and that $0\leq\beta+l\ \hat{x}^{a}\leq1$, when k^{o} and k^{a} are high enough.

From (18) and (19), we can show that

$$\hat{x}^{o}=\sqrt{\left(\frac{k^{a}(1+\beta)}{k^{o}l}+\frac{k^{a}}{k^{o}}\hat{x}^{a}\right)\hat{x}^{a}}. \qquad (22)$$

Proposition 2 *It holds that:*

(*i*) *If $k^{a}\geqslant k^{o}$, or if l is low enough, then $\hat{x}^{o}>\hat{x}^{a}$.*

(*ii*) *If $k^{a}<k^{o}$ and l is high enough, then $\hat{x}^{a}>\hat{x}^{o}$.*

Proof. See Appendix. ■

This proposition carries on interesting results. For $k^{a}>k^{o}$ one expects, to obtain $\hat{x}^{o}>\hat{x}^{a}$. Similarly, if the absorption parameter is too low to allow the firm to benefit from the competitor's R&D, then it makes sense to focus on IR&D. Interestingly, even when $k^{a}=k^{o}$, it still holds true that the firm will invest more in IR&D than in AR&D. Indeed, suppose that $k^{a}=k^{o}$, the free spillover β is zero, and the learning parameter l is very high. In this context, it seems intuitive to expect the socially optimal AR&D level to be higher than the IR&D level. However, we get the opposite result. One explanation is that a higher learning parameter directly increases the efficiency of the investment in AR&D and indirectly increases the efficiency of the investment in IR&D (see expression (1)). Further note that the first result in (i) holds for any value of l, and in particular for a high one. In this case, our result contradicts the one found by simulation in Hammerschmidt (2009) where it is shown that firms invest more in AR&D when the spillover parameter is higher. The result in (ii), stating that $\hat{x}^a > \hat{x}^o$ when $k^a < k^o$ and l is high enough, is intuitive.

The non-linear system (11)-(12) involves two equations and two unknown variables, which are the optimal symmetric R&D levels for the firms and are denoted by x^{*o} and x^{*a}. Since the emissions tax and R&D subsidies are set to induce firms to achieve the socially optimal production and R&D levels, then the optimal emissions tax and R&D subsidies should be chosen such that $\hat{x}^o$ and $\hat{x}^a$ chosen by the regulator are the solution to the equations system (11)-(12). Therefore, from (8), (11) and (12), we have:

$$t = \frac{a - \theta - 3\hat{q}}{1 - (1 + \beta + l\hat{x}^a)\hat{x}^o}, \tag{23}$$

$$\begin{aligned} r^o &= 2k^o\hat{x}^o - \frac{2}{3}t(2 - \beta - l\hat{x}^a)\hat{q}, &(24)\\ r^a &= 2k^a\hat{x}^a - \frac{4}{3}tl\hat{x}^o\hat{q}. &(25)\end{aligned}$$

Thus, we can establish the following proposition:

Proposition 3 *The regulator can induce firms to implement the first-best levels of production and R&D by using the three regulatory instruments, namely a per-unit emissions tax, a per-unit original-research subsidy and a per-unit absorptive-research subsidy.*

From (20) and (21), we can show that

$$\lim_{k^o,k^a \to +\infty} k^o\hat{x}^o = \frac{1}{4}\alpha(1 + \beta)(a - \theta - \alpha), \quad \lim_{k^o,k^a \to +\infty} k^a\hat{x}^a = 0. \tag{26}$$

From (14) and (23), we have

$$\lim_{k^o,k^a \to +\infty} t = \frac{1}{2}\left[3\alpha - (a - \theta)\right] < 0 \Leftrightarrow \alpha < \frac{a - \theta}{3}.$$

Therefore, when the marginal damage of pollution is high enough, the regulator taxes pollution and when it is low enough, he actually subsidizes production to deal with the duopoly distortion.

By using (14), (26), (24) and (25), we deduce:

$$\begin{aligned} \lim_{k^o,k^a \to +\infty} r^o &= \frac{1}{2}(a - \theta - \alpha)\left[(2\beta - 1)\alpha + \frac{(2 - \beta)}{3}(a - \theta)\right], &(27)\\ \lim_{k^o,k^a \to +\infty} r^a &= 0. &(28)\end{aligned}$$

The following proposition compares the subsidy rates for efforts in original and absorptive-capacity R&D.

Proposition 4 *When k^o and k^a are high enough, then:*
(*i*) $r^o > r^a$, *for* $\beta \geq 1/5$, *or* $\beta < 1/5$ *and* α *is low enough;*
(*ii*) $r^o < r^a$, *for* $\beta < 1/5$ *and* α *is high enough.*

Proof. See Appendix. ■

The results in the above proposition are to some extent unexpected. Indeed, consider the case where the free spillover β is zero, l is close to zero, and the marginal damage cost of pollution is high. In this case, where free spillover is absent and spillover benefits are nearly absent, we expect the regulator to subsidize original research at a higher rate to prevent environmental damage. The result in item (*ii*) is actually showing the reverse. This result is very interesting from the environmental point of view. To summarize, the subsidy policy of the regulator consists in trying to induce a minimum level of R&D externalities. Indeed, when the free spillover is high enough, he supports original research, and when it is low enough and the marginal damage of pollution is sufficiently high, he supports absorptive research.

Since $\lim_{k^o,k^a \to +\infty} r^a = 0$, from Proposition 4, we can know when the subsidy for original research is positive or negative (in such a case the regulator actually taxes IR&D). Indeed, when the free spillover is high enough, original research is subsidized. When the free spillover and the marginal damage cost of pollution are low enough, we know that the regulator subsidizes production; this may induce firms to underinvest in IR&D with respect to the socially optimal level, and that is why it is subsidized; however, when the marginal damage cost of pollution is high enough, pollution is taxed which may induce firms to overinvest in IR&D, and that is why it is actually taxed.

5 Conclusion

We consider a duopoly competing in quantity where firms can invest in both original (inventive) and absorptive R&D to control their emissions of pollution. Our objective is to compare the socially optimal R&D levels for original and absorptive research, and to study the behavior of the regulator with regard to these two types of research.

We show that the regulator can induce firms to implement the first best levels of production and R&D by means of three instruments: a tax per-unit of pollution, a subsidy per-unit of inventive R&D and a subsidy per-unit of absorptive R&D. Interestingly, the socially optimal R&D level for original research is higher than the one for absorptive capacity when the investment-cost parameters are equal, the free spillover is zero and the learning parameter is very high. One explanation is that a higher absorptive parameter directly increases the efficiency of the investment in absorptive R&D and indirectly increases the efficiency of the investment in inventive R&D.

Surprisingly, when the free spillover is equal to zero, the marginal damage cost of pollution is high enough and the learning parameter is close to zero, it is expected that the regulator would subsidize original research at a higher rate to prevent environmental damage, but we obtain the opposite result. In fact, through his subsidy policy and in presence of the possibility to invest in absorptive research, the regulator tries to induce a minimum level of R&D externalities. Indeed, when the free spillover is high enough, he gives a higher per-unit subsidy to inventive research, and when it is low enough and the marginal damage cost of pollution is sufficiently high, he gives a higher per-unit subsidy to absorptive research Moreover, the investment in inventive R&D is actually taxed when the free spillover is sufficiently low and the marginal damage cost of pollution is high enough. Clearly, these two last results holding for high marginal damage cost are interesting from the environmental point of view.

6 Appendix

A) Firms' second-order conditions of the second stage

Consider the Hessian Matrix:

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

By using the first-order conditions given by (9)-(10), we can determine the second derivatives constituting matrix H_V 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, $x^o$and x^a (symmetric case).

As $\lim_{k^o,k^a \to +\infty} \hat{x}^o$, $\lim_{k^o,k^a \to +\infty} \hat{x}^a$ and $\lim_{k^o,k^a \to +\infty} t$ 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:

i) $\frac{d^2V_i}{dx_i^{o2}} < 0$ and $\frac{d^2V_i}{dx_i^{a2}} < 0$,

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

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

B) Regulator's second-order conditions of the second stage

Consider the Hessian Matrix:

$$H_S = \begin{pmatrix} \frac{d^2S}{dx^{o2}} & \frac{d^2S}{dx^o dx^a} \\ \frac{d^2S}{dx^o dx^a} & \frac{d^2S}{dx^{a2}} \end{pmatrix}$$

By using the first-order conditions given by (16)-(17), we can compute the second derivatives constituting matrix H_S which can be written as:

$$H_S = \begin{pmatrix} f_1 - 4k^o & f_2 \\ f_2 & f_3 - 4k^a \end{pmatrix},$$

where f_i, $i = 1, 2, 3$, are polynomial functions in x^o and x^a. Since $\lim_{k^o,k^a \to +\infty} \hat{x}^o = \lim_{k^o,k^a \to +\infty} \hat{x}^a = 0$, then f_i take finite values when k^o and k^a tend to $+\infty$.

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

i) $f_1 - 4k^o < 0$ and $f_3 - 4k^a < 0$,

ii) $\det H_S = (f_1 - 4k^o)(f_3 - 4k^a) - f_2^2 > 0$.

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

C) Proof of Proposition 1

Expression (20) can be developed as:

$$\alpha(1+\beta)(a-\theta-\alpha)+\alpha^2(1+\beta)^2x^o+\alpha l\left[a-\theta-\alpha+2\alpha(1+\beta)x^o\right]x^a+\alpha^2l^2x^o(x^a)^2-4k^ox^o=0 \tag{29}$$

From (21), we have:

$$x^a = \frac{\alpha l\left[a-\theta-\alpha+\alpha(1+\beta)x^o\right]x^o}{4k^a-\alpha^2l^2x^{o2}}. \tag{30}$$

By using the expression of x^a given by (30) in (29) and then multiplying by $\left(4k^a - \alpha^2 l^2 x^{o2}\right)^2$, we get a polynomial function of degree 5 in x^o: $Q(x^o) = 0$.

The coefficient of x^{o5} is $-4\alpha^4 l^4 k^o$, and the constant term is $16\alpha(1+\beta)(a-\theta-\alpha)k^{a2}$.

Since $Q(0) > 0$ and $\lim_{x^o \to +\infty} Q(x^o) = -\infty$, then $Q(x^o)$ admits at least one real and positive root $\hat{x}^o > 0$, and admits at most five roots. Because of (3), (15) and (30), $\hat{x}^a > 0$ when k^o and k^a are high enough.

D) Proof of Proposition 2

From expression (22), we deduce the following:

i) If $k^o \le k^a$, then $\hat{x}^o > \hat{x}^a$.

ii) If $k^a < k^o$, then

$$\hat{x}^o < \hat{x}^a \Leftrightarrow \frac{k^a\left(1+\beta+l\hat{x}^a\right)}{k^o l} < \hat{x}^a \Leftrightarrow \hat{x}^a > \frac{k^a\left(1+\beta\right)}{\left(k^o-k^a\right)l}.$$

If l is high enough, then $\hat{x}^o < \hat{x}^a$. If l is low enough, then it is the other way around ($\hat{x}^o > \hat{x}^a$).

E) Proof of Proposition 4

From (27) and (28):

$$\lim_{k^o,k^a \to +\infty} r^o > \lim_{k^o,k^a \to +\infty} r^a \Leftrightarrow (2\beta-1)\alpha + \tfrac{2-\beta}{3}(a-\theta) > 0.$$

i) The above inequality is always satisfied when $\beta \geqslant 1/2$...

ii) Suppose that $\beta < 1/2$;

· $\lim_{k^o,k^a\to+\infty} r^o > \lim_{k^o,k^a\to+\infty} r^a \Leftrightarrow \alpha < \frac{2-\beta}{3(1-2\beta)}(a-\theta)$; because of condition 15, this last inequality is always verified when $\beta \geq 1/5$, and when $\beta < 1/5$, we need α to be sufficiently low.

·· $\lim_{k^o,k^a\to+\infty} r^o < \lim_{k^o,k^a\to+\infty} r^a \Leftrightarrow \alpha > \frac{2-\beta}{3(1-2\beta)}(a-\theta)$; this last inequality is not in contradiction with (15) when $\beta < 1/5$.

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