Environmental R&D in the Presence of an Eco-Industry

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Abstract: We compare the performance of R&D cooperation and R&D competition within the eco-industry using a model of vertical relationship between a polluting industry and the eco-industry. The polluting industry is assumed perfectly competitive and the eco-industry is a duopoly in the market for abatement goods and services, with one firm acting as a Stackelberg leader and the other firm as a follower. When there are full information sharing under R&D cooperation and involuntary information leakages under R&D competition, we find that the only case where government intervention is needed is the case where R&D cooperation yields a higher welfare but smaller profits for the follower eco-industrial firm than R&D competition. Furthermore, because of the market power that the eco-industry enjoys, we show that more total R&D efforts under R&D competition do not necessarily translate into more abatement activities and larger social welfare. When there are no involuntary leakages of information under R&D competition, this result occurs because R&D competition can induce more total R&D efforts than R&D cooperation even for significantly high R&D spillovers if the marginal environmental damage is large.

Keywords: Eco-industry; Environmental R&D; R&D cooperation; Environmental R&D outsourcing; Upstream innovation.

JEL Classifications: L13;O32; Q55; Q58.

1. Introduction

There is a growing interest in the study of the organization of environmental R&D (R&D cooperation versus R&D competition) in the environmental economics literature [see, e.g., Hackett (1995), Scott (1996, 2005), Katsoulacos and Ulph (2001), Chiou and Hu (2001), Poyago-Theotoky (2007, 2010), and Liu (2011)]. This strand of literature shows that the welfare ranking of cooperative and competitive R&D in the standard industrial organization literature[1] needs to be nuanced when innovations deal with environmental matters, since adding in environmental externalities involves additional market failures.

In the standard set-up of these previous studies, environmental R&D takes place within polluting firms. In practice, however, most of environmental innovations occur outside of the polluting industries. At the global level, 80% of the patents for controlling pollution originate in specialized firms (Lanjouw and Mody, 1996), which constitute the so-called eco-industry[2]. At a more specific level, the US electric utility industry procures its entire pollution control equipment from upstream electric equipment manufactures, such as General Electric (Sanyal and Ghosh, 2010). A similar claim is put forward by Hanemann (2009) who, citing Taylor (2008), provides evidence of R&D outsourcing for SO2 control by US electric utilities and oil companies. In line with this evidence for environmental R&D outsourcing, and in view of the current figures concerning the revenues from the eco-industry[3], this paper analyzes the organization of environmental R&D within the eco-industry by comparing the performance of R&D cooperation and R&D competition in

[1] This industrial organization literature focuses on how technological spillovers affect the comparison of R&D cooperation and R&D competition in terms of R&D efforts, profits of the firms, and social welfare [see, e.g., d'Aspremont and Jacquemin (1988, 1990), Henriques (1990), Kamien et al. (1992), Suzumura (1992), etc.]. This literature argues that R&D cooperation increases R&D efforts, and is thus welfare improving, when technological spillovers are sufficiently high. Amir et al. (2002) extend this literature to include the comparison of R&D cooperation versus monopoly.

[2] The Organization for Economic Cooperation and Development defines the eco-industry as the set of "(...) activities which produce goods and services to measure, prevent, limit, minimize or correct environmental damage to water, air, and soil, as well as problems related to waste, noise and eco-systems." [OECD/Eurostat (1999)]

[3] For precise information about the evolution of the eco-industry, as well as a short history of the sector and a discussion of its definition, see Sinclair-Desgagné (2008).

terms of total R&D efforts, total abatement activities, eco-industry profitability, and social welfare. Throughout, we concentrate on two special cases of R&D spillovers. The first case assumes that there are no involuntary leakages of information when eco-industrial firms compete in R&D. The second case presumes that eco-industrial firms fully share information when they cooperate in R&D and that there are involuntary information leakages under R&D competition.

We consider a setting where a perfectly competitive polluting industry procures abatement goods and services (AGS) from a duopolistic eco-industry. The two eco-industrial firms are conducting cost-reducing R&D either cooperatively or competitively. After their R&D decisions, they engage in Stackelberg competition in the market for AGS. The use of a Stackelberg framework is inspired by evidence that some eco-industrial firms enjoy first-mover advantages in the market for AGS. The Environmental Business International (2011, p. 98), for example, reports that:

> *"Those firms with strong existing client relationships - as well as reputation for having good relationships with regulators - continue to have the inside track in key industrial and government client segments."*

Indeed, eco-industrial firms do not enter the market at the same time, a situation which naturally leads to opportunities for first-mover advantage. By the time the new entrants in the eco-industry pull out of production, preexistent firms would have already established strong reputation. Furthermore, since polluting firms have to make initial costly investments in equipment and technical training, and because eco-industrial firms provide services on a contractual basis, abatement activities generally involve significant switching costs. On the supply side, the presence of high start-up costs results in an imperfectly competitive market structure, and can provide incumbent eco-industrial firms with long-lasting large market share (Baumol, 1995). For example, Waste Management Inc. has maintained its leading position over time in the US solid waste management segment of the eco-industry, with a market share of about 23% in 2009 (Environmental Business International, 2011). In turn, GE Water & Process Technologies and Babcock and Wilcox Co. are the leading companies in the water and wastewater treatment and the air pollution control equipment segments of the US eco-industry. Despite entry of new firms, incumbents' market share seem to remain relatively high. For these reasons, we use a Stackelberg model for the eco-industry where the incumbents are assumed to be Stackelberg leaders.

We derive three main results. First, we find that whether the eco-industry or society as a whole prefers R&D cooperation over R&D competition depends on the combination of the level of the marginal damage from pollution and the degree of R&D spillovers. At the heart of the role of the marginal damage is the fact that high marginal damages induce stringent regulations, which increase the market power of the eco-industry. In this context, eco-industrial firms might exploit their market power by strategically choosing their R&D investments to increase their mark-ups with direct consequences for the environment and society. Second, we show that government incentives might be required to encourage environmental R&D cooperation. Indeed, in the case when there are no involuntary information leakages under R&D competition, the leader eco-industrial firm may not want to cooperate over R&D whereas the follower always wants to cooperate. In contrast, in the case when there are full information sharing under R&D cooperation and involuntary information leakages under R&D competition, it is the follower who may not want to cooperate over R&D whereas the leader always wants to cooperate. In this last case where R&D cooperation yields a higher welfare but smaller profits for the follower eco-industrial firm than R&D competition, there is scope for government intervention, for example by strengthening intellectual property rights. Finally, we show that more R&D investments under R&D competition do not necessarily result in more abatement activities and a larger social welfare. In the case when there are no involuntary information leakages under R&D competition, this divergence arises because R&D competition can induce more total R&D efforts than R&D cooperation even for significantly high levels of R&D spillovers, in contrast to the previous literature. In fact, for sufficiently large marginal environmental damages , eco-industrial firms competing in R&D attempt to capture all the rents from innovation to the detriment of the environment and society.

A thorough understanding of the impact of this vertical industrial organization - where environmental R&D is done by the upstream eco-industry that supplies pollution abatement equipment to downstream polluters - is important for regulatory authorities as they choose a target variable for environmental innovation policy. For instance, policymakers should exercise caution when using the total level of environmental R&D expenditures in the eco-industry as a target variable since more R&D efforts do not necessarily translate into more abatement activities and more social welfare. Such understanding is also important for regulators as they assess the merits of different innovation policies that aim to encourage environmental R&D cooperation. For example, the Technology Strategy Board, the UK public body charged with the responsibility to promote innovation, has been promoting R&D collaboration in strategically important areas of science, engineering, and technology - such as environmental sustainability - through its Collaborative Research and Development (CR&D) program.[4] Another example of an environmental R&D cooperation initiative is the Electric Power Research Institute (EPRI), whose mandate is to coordinate multi-company collaborative R&D within the energy sector.[5] Our results suggest that the success of any environmental R&D policy relies on the ability of regulators to understand the eco-industry's strategic innovation behavior. In particular, the presence of the eco-industry as well as the interactive effect of the level of marginal environmental damage and the degree of R&D spillovers on the eco-industry's innovation behavior are important in the choice of the suitable policy.

Before proceeding, we briefly review previous work that is closely related to our paper. Scott (1996, 2005), Katsoulacos and Ulph (2001), Chiou and Hu (2001) and Poyago-Theotoky (2007) pay particular attention to how polluting firms organize their environmental R&D and analyze the underlying environmental and/or economic consequences of different R&D organization regimes. In a more recent work, Liu (2011) analyzes the

[4] The CR&D program provides, on a competitive basis, grants of between 25 and 75 percent of total R&D costs for projects involving two or more collaborators. For more details on the CR&D program, see http//www.innovateuk.org/deliveringinnovation/collaborativeresearchanddevelopment.ashx, (accessed on February 4, 2011).

[5] We thank David Popp for suggesting this example.

strategic interactions between environmental innovation behaviors of two vertically related polluting industries. We build on these previous studies by developing a vertical organization structure set-up where environmental R&D is outsourced to the eco-industry. We also differ from these previous works in two additional ways. First, we focus on process innovation through which the eco-industry seeks to reduce the cost of producing AGS.[6] Second, unlike the previous literature which typically considers a symmetric Cournot duopoly model and for the reasons given above, we investigate a Stackelberg duopoly case where one eco-industrial firm acts as a leader in the production stage.[7]

A still-growing literature in environmental economics also explicitly takes account of the presence of an eco-industry.[8] However, to the best of our knowledge, our paper constitutes the first attempt to study the organization of environmental R&D (R&D cooperation versus R&D competition) as occurring in an upstream eco-industry. Of course, the industrial organization literature has devoted considerable attention to the organization of R&D in vertically-related industries that produce conventional inputs and outputs.[9] With the exception of Atallah (2002), previous papers have not modeled the parallel issue of horizontal R&D cooperation in the upstream industry. In contrast with Atallah (2002),[10] our model focuses only on horizontal R&D cooperation in the upstream eco-industry. Our framework allows us to capture two important features of the eco-industry. First,

[6] As pointed out by Katsoulacos and Ulph (1998), spillovers associated with process innovation are in general higher than spillovers from product innovation.

[7] We also analyzed the impact on the organization of environmental R&D of the presence of the eco-industry when the latter engages in Cournot competition in the AGS market. We also find some discrepancy in the comparison of the performance of R&D cooperation and R&D competition in terms of R&D efforts, abatement activities (and thus environmental quality), eco-industry's profits, and social welfare. However, whenever government intervention is needed, we find that it is always aimed at imposing R&D competition within the eco-industry.

[8] See, e.g., Parry (1995), Biglaiser and Horowitz (1995), Laffont and Tirole (1996a, 1996b), Denicolo (1999), Feess and Muehlheusser (2002), David and Sinclair-Desgagné (2005, 2010), Greaker (2006), Canton et al. (2008), Greaker and Rosendahl (2008), Golombek et al. (2010), Perino (2010), David et al. (2011), Nimubona and Sinclair-Desgagné (2011, 2013), Heyes and Kapur (2011), and Greaker and Hoel (2011).

[9] See, e.g., Banerjee and Lin (2001, 2003), Atallah (2002), Brocas (2003), Ishii (2004), Versaevel and Vencatachellum (2009), and Chen and Sappington (2010).

[10] Atallah (2002) develops a model that incorporates two vertically related industries with horizontal spillovers within each industry and vertical spillovers between the two industries.

abatement goods and services are different from traditional inputs. As they are only used in order to alleviate environmental externalities, their demand is pulled by environmental regulations. Second, as pointed out by Sanyal and Ghosh (2010) in the case of the US electricity industry, the vertical relationships between polluters and the eco-industry involve industries that engage in completely different core activities. As a consequence, there is not much room for the presence of vertical R&D spillovers between polluting and eco-industries.

The remainder of our analysis is structured as follows. Section 2 presents our model and some preliminary results. In particular, we characterize the equilibrium under R&D cooperation and R&D competition. In section 3, we then turn to the comparison of the two R&D regimes first in terms of eco-industry profitability and social welfare, and then in terms of R&D efforts and abatement activities. Section 4 concludes our analysis. Finally, the appendix section provides explicit formulas for our endogenous variables and proofs not included in the text.

2. The model and some preliminaries

We consider a setting in which a perfectly competitive polluting industry is vertically related to a duopolistic eco-industry in the presence of an emission tax. A representative price-taking polluting firm produces and sells a consumption good x at a unit price P. The market demand for good x is given by: $P = \alpha - x$, with $\alpha > 0$. Let $C(x) = cx$ be the representative polluting firm's production cost function, where c is the unit cost of production (there are constant returns to production). For simplification, we assume that $c = 0$. Production generates pollution and the emissions per output ratio is assumed to be equal to 1 in the absence of pollution abatement. A unit of emissions is taxed by the government at a rate t. However, polluting firms have the option of abating their pollution by using abatement goods and services (AGS) supplied by the eco-industry. The amount of pollution that is abated by using a quantity A of AGS is given by $\xi A - \frac{1}{2}A^2$, where the parameter ξ represents a fixed marginal efficiency of AGS.

The net emissions e generated by the production of x units of output are thus given by $e(x, A) = Max\left\{0, x - \left(\xi A - \frac{1}{2}A^2\right)\right\}$. We assume that $0 < A < \xi$, which implies that AGS reduce pollution ($e_A < 0$), and that there are decreasing returns to abatement ($e_{AA} > 0$).

The two eco-industrial firms produce a homogeneous product. The cost of producing a_i amount of AGS for eco-industrial firm i is ga_i, with $g > 0$. The eco-industrial firms behave as Stackelberg players in the production stage.[11] Prior to that, these eco-industrial firms simultaneously determine their levels of R&D effort to reduce the cost of supplying AGS.[12] We consider that eco-industrial firms can either compete or cooperate when investing in cost reducing R&D. The cost of undertaking y_i R&D effort for firm i is given by $\frac{1}{2}y_i^2$, i.e., R&D is characterized by decreasing returns. Therefore, the total cost for eco-industrial firm i of supplying an amount of AGS equal to a_i and undertaking a level of R&D effort equal to y_i is given by $G_i(a_i, y_i, y_j) = (g - y_i - \omega y_j)\, a_i + \frac{1}{2}y_i^2$, with $g > y_i + \omega y_j$ and $i \neq j$. The variable y_j is the level of R&D that a rival firm j undertakes and $\omega \in [0, 1]$ is the R&D spillover level, which is assumed to be exogenous.

As highlighted by Kamien et al. (1992) and Katsoulacos and Ulph (1998), among others, R&D cooperation is likely to maximize the level of information sharing, and thus to involve a higher level of R&D spillovers than R&D competition. To account for this fact, we consider that the level of R&D spillovers when eco-industrial firms compete in R&D, which denotes as $\omega_{\min}$, is lower than or equal to the one under R&D cooperation, which we denote as $\omega_{\max}$ ($\omega_{\min} \leqslant \omega_{\max}$). In this perspective, we analyze two different but

[11] The previous literature, which analyzes the organization of environmental R&D in the polluting industry, considers instead a Cournot duopoly model [see, e.g., Chiou and Hu (2001), Poyago-Theotoky (2007)]. Surely, the Cournot case constitutes an interesting framework for the analysis of a polluting industry. However, as we argue in the introduction section of this paper, typical eco-industrial firms are not expected to behave as Cournot competitors.

[12] Amir et al. (2000) compare the outcomes of simultaneous versus sequential moves in the R&D stage of the R&D competition game. They characterize the R&D leader and follower behaviors while assuming simultaneous-move at the final good production stage. In contrast, this paper features the first-move advantages at the AGS production stage while keeping simultaneous move in the R&D stage. Lambertini et al (2004) model the production process as a Stackelberg game. However, they do not consider R&D outsourcing as they examine the case where R&D is undertaken by the producers of the final good.

complementary cases of R&D spillovers. In the first case, we assume on one hand, and following Brander and Spencer (1983), that $\omega_{\min} = 0$ when eco-industrial firms compete in R&D: we exclude the possibility of involuntary information leakages. This corresponds to a situation where a perfectly functioning patent system is in place. On another hand, when eco-industrial firms cooperate in R&D, we have $0 \leqslant \omega_{\max} = \omega \leqslant 1$. We allow for $\omega_{\max} < 1$ under R&D cooperation to acknowledge that cooperative eco-industrial firms can partly share their R&D information. In the second case, we assume, as in Atallah (2007) and Leahy and Neary (2007), that R&D spillovers are given by $0 \leqslant \omega_{\min} = \omega \leqslant 1$ and $\omega_{\max} = 1$ when eco-industrial firms compete and cooperate in R&D, respectively. This last case corresponds to a situation with involuntary information leakages under R&D competition, and complete information sharing under R&D cooperation.[13]

The game unfolds as follows. In the first stage, the two eco-industrial firms choose their respective levels of cost-reducing R&D, either cooperatively or competitively. In the second stage, eco-industrial firms anticipate the demand for AGS and engage in a Stackelberg competition to choose the quantities of AGS they will produce. In the last stage, polluting firms choose the amount of AGS they will buy as well as their optimal level of production, given the emission tax and the price of AGS. The equilibrium price of AGS is the market-clearing price where the quantity of AGS demanded by the polluting firms just equals the quantity supplied by the eco-industry.

To determine a subgame perfect Nash equilibrium, we first solve for the equilibrium in the polluting industry. In this last stage of our game, a representative polluting firm solves the following maximization problem

$$\max_{x,A} \pi(x, A) = Px - pA - t \left[x - \left(\xi - \frac{A}{2} \right) A \right] \ , \tag{1}$$

where p denotes the price of AGS. The equilibrium in the market for the polluting good

[13] Considering R&D spillovers as endogenous, Poyago-Theotoky (1999) argues that it is always optimal for duopolistic firms to set $\omega = 0$ and $\omega = 1$ when they compete and cooperate in the R&D stage, respectively.

is characterized by the following market-clearing condition:

$$P - t = 0 \ . \tag{2}$$

Equation (2) yields the equilibrium output level of the polluting industry, $x^* = \alpha - t$, which is equally distributed to a continuum of polluting firms with size one. We assume that $t < \alpha$ to ensure that the equilibrium value for x is positive. Given its equilibrium level of production, a representative polluting firm then chooses its optimal level of abatement according to the following first-order condition:

$$-p + t\xi - tA = 0 \ . \tag{3}$$

Equation (3) gives the inverse demand function for abatement: $p(A) = t\,(\xi - A)$.[14]

We consider in turn two different cases for the R&D behavior of eco-industrial firms: R&D cooperation and R&D competition.

2.1. Eco-industrial firms cooperate in R&D

Eco-industrial firms engage in a two-stage duopolistic subgame where they first choose their cooperative levels of cost-reducing R&D, and then choose their production levels. In the production stage, given the vector of R&D efforts (y_1, y_2) and the inverse demand for AGS derived from (3), the eco-industrial firms play a Stackelberg game. Let us assume that eco-industrial firm 1 is the Stackelberg leader. The leader eco-industrial firm's problem is

$$\max_{a_1} \pi_1 = t\,[\xi - (a_1 + a_2)]\,a_1 - (g - y_1 - \omega y_2)\,a_1 - \frac{1}{2}y_1^2 \ , \tag{4}$$

subject to the constraint of the follower's reaction function

$$a_2 = \frac{(t\xi - g) + y_2 + \omega y_1 - ta_1}{2t}. \tag{5}$$

[14] It can be shown that this inverse demand function for abatement is decreasing in A, i.e. $p_A < 0$. Moreover, a tax rise will generate a clockwise rotation of the inverse demand curve with respect to its horizontal intercept, i.e. $p_t > 0$ and $p_{At} \leq 0$ [see David et al. (2011)].

The Stackelberg equilibrium is thus

$$a_1 = \frac{(t\xi - g) + (2-\omega)\, y_1 + (2\omega - 1)\, y_2}{2t} \tag{6}$$

$$a_2 = \frac{(t\xi - g) + (3\omega-2)\, y_1 + (3 - 2\omega)\, y_2}{4t}. \tag{7}$$

In the R&D stage, which precedes the above noncooperative choice of production levels, eco-industrial firms' profits can now be written as

$$\pi_1 = \Phi\Psi_1 - \frac{(g - y_1 - \omega y_2)}{t}\Psi_1 - \frac{1}{2}y_1^2 \tag{8}$$

$$\pi_2 = \Phi\Psi_2 - \frac{(g - y_2 - \omega y_1)}{t}\Psi_2 - \frac{1}{2}y_2^2 \tag{9}$$

where

$$\Phi \equiv \xi - \frac{3\,(t\xi - g) + (\omega+2)\, y_1 + (2\omega + 1)\, y_2}{4t},$$

$$\Psi_1 \equiv \frac{(t\xi - g) + (2-\omega)\, y_1 + (2\omega - 1)\, y_2}{2},$$

$$\text{and} \quad \Psi_2 \equiv \frac{(t\xi - g) + (3\omega-2)\, y_1 + (3 - 2\omega)\, y_2}{4}.$$

When eco-industrial firms cooperate in R&D, they choose their R&D levels by maximizing their joint profits, $\Pi = \pi_1 + \pi_2$. We assume away the possibility that eco-industrial firms could make transfers to each other as this would encourage collusion in the AGS market. Only contributions to R&D are possible. For simplicity, we analyze the case in which both firms make equal contributions.[15] This assumption seems appropriate as the eco-industrial firms equally share the benefits from R&D. Therefore, we are looking for a symmetric equilibrium solution $y_1^{CS^*} = y_2^{CS^*} = y^{CS^*}$, where the superscript CS stands for Cooperation in R&D under Stackelberg competition in output, which satisfies the first order condition for the maximization of Π. The full equilibrium under R&D cooperation

[15] It is worth noting that the case in which R&D contributions are asymmetric can also be envisaged. As suggested by Lambertini et al. (2004) for the distribution of profits, R&D expenditures could be alternatively shared according to a Nash bargaining solution or in proportion to the asymmetric firms' market shares. However, this would entail significant difficulties as one will need to take into account the firms' commitment and agreement to share R&D costs.

is described by the system of equations (A.1) in Appendix A.

The game in the R&D cooperation case has an interior equilibrium with positive values under the following conditions: (i) $t\xi > g$ and (ii) $\frac{9}{8} < t < \alpha$.[16] These two inequalities imply that production in the eco-industry is profitable. The bottom line of these conditions is that α needs to be large enough to guarantee positive output and emissions, and that t must not be too small to guarantee that there are enough incentives to abate and conduct environmental R&D. Under these conditions, we can observe that $a_1^{CS^*} > a_2^{CS^*}$ and $\pi_1^{CS^*} > \pi_2^{CS^*}$.

The next subsection analyzes the eco-industry's equilibrium under the environmental R&D competition regime.

2.2. Eco-industrial firms compete in R&D

Within this framework, the behavior of the polluting industry remains the same. However, the remaining stages of the game need to be adjusted for the R&D behavior of the eco-industry. In the production stage, the equilibrium output level of the leader eco-industrial firm corresponds now to the solution of the following program

$$\max_{a_1} \pi_1 = t\left[\xi - (a_1 + a_2)\right] a_1 - (g - y_1 - \omega y_2)\, a_1 - \frac{1}{2} y_1^2 \ , \tag{10}$$

subject to the constraint of the follower's reaction function

$$a_2 = \frac{(t\xi - g) + y_2 + \omega y_1 - t a_1}{2t} \ . \tag{11}$$

Taking R&D levels as given, the equilibrium in the production stage is as follows

$$a_1 = \frac{(t\xi - g) + (2 - \omega)\, y_1 + (2\omega - 1)\, y_2}{2t} \tag{12}$$

$$a_2 = \frac{(t\xi - g) - (2 - 3\omega)\, y_1 + (3 - 2\omega)\, y_2}{4t}. \tag{13}$$

[16] If condition (ii) is verified, then the second order condition for optimal R&D investment, given by $16t - 3(\omega + 1)^2 > 0$, is verified for any $\omega \epsilon [0, 1]$. We thank an anonymous referee for bringing this to our attention.

In the R&D stage, eco-industrial firms 1 and 2 now seek to maximize their own profits, which can respectively be written as

$$\pi_1 = \Gamma\Delta_1 - \frac{(g - y_1 - \omega y_2)}{t}\Delta_1 - \frac{1}{2}y_1^2 \quad (14)$$

$$\pi_2 = \Gamma\Delta_2 - \frac{(g - y_2 - \omega y_1)}{t}\Delta_2 - \frac{1}{2}y_2^2 \quad (15)$$

where

$$\Gamma = \xi - \frac{3(t\xi - g) + (2+\omega)y_1 + (1+2\omega)y_2}{4t},$$

$$\Delta_1 = \frac{(t\xi - g) + (2-\omega)y_1 + (2\omega - 1)y_2}{2},$$

$$\text{and } \Delta_2 = \frac{(t\xi - g) - (2-3\omega)y_1 + (3-2\omega)y_2}{4}.$$

The equilibrium R&D efforts of firms 1 and 2, which we denote by $y_1^{NS^*}$ and $y_2^{NS^*}$ where the superscript NS stands for Noncooperation in R&D under Stackelberg competition in output, solve the corresponding first order conditions for optimal R&D investment. The full equilibrium is described by the system of equations (A.2) in Appendix A.

The R&D competition case has an interior equilibrium with positive values under the following conditions: (i) $t\xi > g$ and (ii) $2 < t < \alpha$.[17] The two inequalities ensure that production in the eco-industry is profitable. In this context, it is immediate to see that $y_1^{NS^*} > y_2^{NS^*}$, $a_1^{NS^*} > a_2^{NS^*}$ and $\pi_1^{NS^*} > \pi_2^{NS^*}$.

To conclude this section, note that the equilibrium quantities of AGS A^{CS^*} and A^{NS^*}depend on ξ (see Appendix A), and recall that $A < \xi < 0$ by assumption. The assumption that $\xi > A^{NS^*}$ is always satisfied for all our interior solutions. In order for $\xi > A^{CS^*}$ to hold for our interior solutions, an extra condition on the value of t is imposed, i.e. $t > 3$.

Assumption 1: *Throughout the rest of the paper, we shall focus on the set of parameters such that conditions (i)* $t\xi > g$ and (ii) $3 < t < \alpha$ hold.

[17]If condition (ii) is verified, then the leader's and the follower's second order conditions for optimal R&D investment, respectively given by $4t - (\omega - 2)^2 > 0$ and $8t - (2\omega - 3)^2 > 0$, are verified for any $\omega \epsilon [0, 1]$.

With the above background, we can now turn to the comparison between the R&D cooperation and R&D competition equilibrium outcomes. We first compare the two R&D regimes in terms of eco-industry profitability and social welfare. We then proceed to compare the equilibrium levels of R&D efforts, abatement activities, and emission levels. For each comparison, we distinguish between two cases: the case when $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$, and the case when $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$. Recall that $\omega_{\min} = 0$ implies that there is no involuntary leakage of information when eco-industrial firms compete in R&D. In turn, $\omega_{\max} = 1$ implies that eco-industrial firms fully share R&D information when they cooperation in the R&D game.

3. Comparing the environmental R&D regimes

3.1. Eco-industry profitability and welfare effects

Let us first compute the social welfare level under each of the two R&D regimes. For tractability, we assume that the marginal social damage from pollution - denoted by d - is constant, and the emission tax is set to be equal to the Pigouvian level, i.e. $t = d$. We limit the range of d such that Assumption 1 is satisfied, i.e. $3 < d < \alpha$. Thus, social welfare is the sum of consumer surplus, the representative polluter's profit and the eco-industry's profit, minus the value of the damage inflicted by the emissions,

$$W = \int_0^x (\alpha - u)\,\mathrm{d}u - G_1(a_1, y_1, y_2) - G_2(a_2, y_2, y_1) - d\left(x - \left(\xi - \frac{1}{2}A\right)A\right). \quad (16)$$

Expressions (A.3) and (A.4) in Appendix A give the equilibrium level of social welfare under R&D cooperation and R&D competition, respectively.

3.1.1. Case 1: $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$

The result of the comparison of R&D cooperation and R&D competition, when $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$, based on the eco-industry's profit and social welfare is recorded in lemma 1 below.

Lemma 1. *For $\omega_{\max} = \omega \in [0,1]$, $\omega_{\min} = 0$, and $d \in]3, \alpha[$,*

1. $\pi_2^{CS^*} > \pi_2^{NS^*}$;

2. *There exists $d_{\pi_1} \in]3, \alpha[$ and $\omega_{\pi_1} \in [0, 0.42]$, such that $\pi_1^{CS^*} < \pi_1^{NS^*}$ ($\pi_1^{CS^*} > \pi_1^{NS^*}$) if one of the following holds: (i) $\omega < \omega_{\pi_1}$ ($\omega > 0.42$), (ii) $\omega_{\pi_1} < \omega < 0.42$ and $d < d_{\pi_1}$ ($\omega_{\pi_1} < \omega < 0.42$ and $d > d_{\pi_1}$);*

3. *There exists $d_W \in]3, \alpha[$ and $\omega_W \in [0, 0.37]$, such that $W^{CS^*} < W^{NS^*}$ ($W^{CS^*} > W^{NS^*}$), if one of the following holds: (i) $\omega < \omega_W$ ($\omega > 0.37$), (ii) $\omega_W < \omega < 0.37$ and $d < d_W$ ($\omega_W < \omega < 0.37$ and $d > d_W$).*

Proof. See Appendix B.

Lemma 1 states that the follower eco-industrial firm's profit is always larger under R&D cooperation than under R&D competition for $\omega_{\max} = \omega \in [0,1]$, $\omega_{\min} = 0$, and $d \in]3, \alpha[$. However, the leader eco-industrial firm's profit may be larger under R&D competition than under R&D cooperation. We consider that R&D cooperation takes place if both firms gain from cooperation. Since the follower firm always gains from R&D cooperation, it is the leader's gain from cooperation that will be important to analyze. Interestingly, the comparison of the leader eco-industrial firm's profits and social welfare levels do not always induce the same ranking of R&D cooperation and R&D competition. Lemma 1 shows that both the level of the marginal environmental damage and the degree of R&D spillovers influence the preferences of both the leader eco-industrial firm and society over the two types of R&D regimes.

Figure 1 below illustrates our findings in Lemma 1 in the (ω, d) space (for $\omega \in [0,1]$, and $d \in]3, \alpha[$). For the graphical analysis, we assume, without loss of generality, that $\alpha = 10$. Let $\Delta\pi_1 = \pi_1^{CS^*} - \pi_1^{NS^*}$ and $\Delta W = W^{CS^*} - W^{NS^*}$. The two curves in the figure represent the pairs (ω, d) for which $\Delta\pi_1 = 0$ (the dashed curve) and $\Delta W = 0$ (the solid curve). The pairs of (ω, d) lying above (below) the curve $\Delta W = 0$ characterize cases where social welfare is higher (lower) under R&D cooperation than under R&D

competition. Similarly, above (below) the curve $\Delta\pi_1 = 0$, R&D cooperation induces more (less) profit for the leader eco-industrial firm than R&D competition. The figure shows that R&D cooperation is always desirable (undesirable) from the social standpoint when the level of R&D spillovers ω is above 0.37 (below 0.31), and that R&D cooperation is always desirable (undesirable) from the leader eco-industrial firm standpoint when the level of R&D spillovers ω is above 0.42 (below 0.09). For R&D spillovers between 0.31 and 0.37 for social welfare and for R&D spillovers between 0.09 and 0.42 for the leader eco-industrial firm, R&D cooperation is desirable (undesirable) from the social standpoint when the marginal damage is above (below) some specific threshold, which is decreasing as the level of R&D spillovers increases. There is an intuitive explanation to the role of the marginal damage. In fact, high marginal damages induce stringent regulations, which increase the market power of the eco-industry. In such cases, eco-industrial firms that engage in R&D competition might exploit their market power by investing more in R&D to increase their mark-ups, which might decrease the quality of the environment and social welfare.

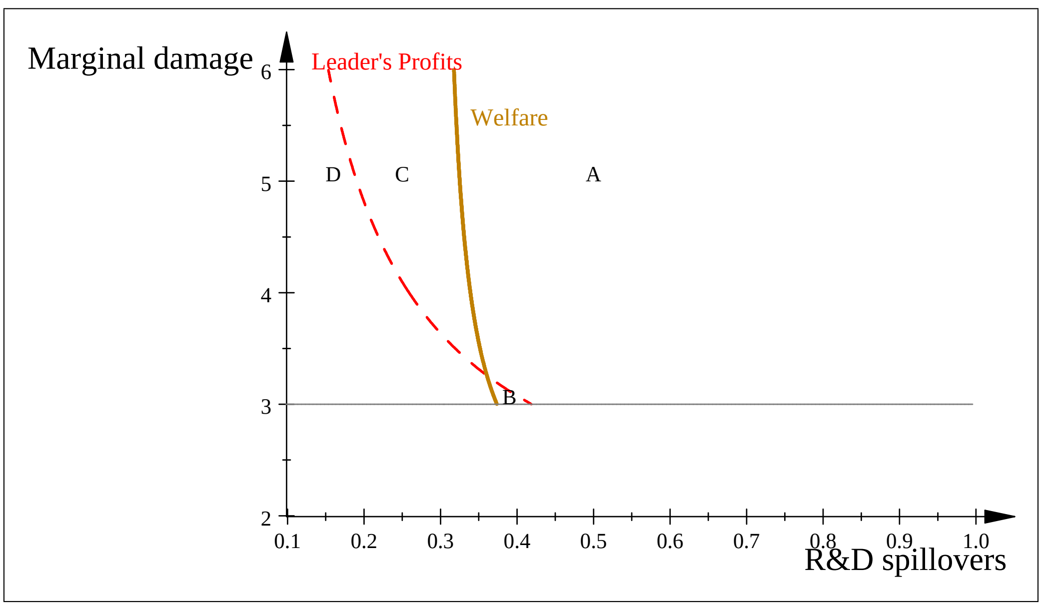

Fig. 1 . Leader's profitability and social welfare when $\omega_{\max} = \omega \in [0, 1]$, $\omega_{\min} = 0$, and $\alpha = 10$.

A further analysis of lemma 1 and figure 1 can help identify circumstances in which there is room for government intervention in the organization of environmental R&D (i.e.

when there is a conflict between the preferences of the leader eco-industrial firm and society). The two curves in Figure 1 divide the space of (ω, d) under consideration, into four disjoint regions - denoted by A, B, C, and D - which correspond to specific rankings of the R&D regimes. Table 1 below characterizes each of these four regions.

Table 1 - Ranking of the R&D Regimes according to eco-industry profitability and social welfare when $\omega_{\max} = \omega \in [0, 1]$, $\omega_{\min} = 0$, and $\alpha = 10$

Region A	Region B	Region C	Region D
$\pi_1^{CS*} > \pi_1^{NS*}$	$\pi_1^{CS*} < \pi_1^{NS*}$	$\pi_1^{CS*} > \pi_1^{NS*}$	$\pi_1^{CS*} < \pi_1^{NS*}$
$\pi_2^{CS*} > \pi_2^{NS*}$	$\pi_2^{CS*} > \pi_2^{NS*}$	$\pi_2^{CS*} > \pi_2^{NS*}$	$\pi_2^{CS*} > \pi_2^{NS*}$
$W^{CS*} > W^{NS*}$	$W^{CS*} > W^{NS*}$	$W^{CS*} < W^{NS*}$	$W^{CS*} < W^{NS*}$

Regions A and D represent pairs of (ω, d) for which the leader eco-industrial firm's interests coincide with social interests.[18] Regions B and C represent pairs of (ω, d) for which the leader eco-industrial firm's interests do conflict with social ones. More precisely, in region B (region C), the leader eco-industrial firm would prefer R&D competition (R&D cooperation) while a regulator maximizing social welfare would prefer R&D cooperation (R&D competition). This result has an interesting policy implication, namely that government policy can be used to align conflicting preferences of the leader eco-industrial firm and society over the organization of environmental R&D. The different types of government intervention that are required are summarized in Proposition 1.

Proposition 1. *Suppose that there is no involuntary information leakage ($\omega_{\min} = 0$) under R&D competition between eco-industrial firms that engage in Stackelberg competition in the market for AGS. If a government intervention is needed to coordinate the organization of R&D in the eco-industry, public policy can take one of the following two options: (i) Induce the leader eco-industrial firm to engage in an otherwise unprofitable*

[18] In region A, R&D cooperation occurs in equilibrium, an outcome which is desirable from both the leader eco-industrial firm and social standpoints. In region D, it is R&D competition that takes place instead, as the preferred R&D regime by both sides.

R&D cooperation that is desirable for society; (ii) Prevent an R&D cooperation that is profitable for the eco-industry but undesirable for society.

Indeed, from any situation with conflicting preferences between the leader eco-industrial firm and society, the government could subsidize R&D cooperation or implement a perfectly functioning patent system in order to maximize or minimize information sharing. The aim of such innovation policy measures would be to make R&D cooperation or R&D competition both profitable for the leader eco-industrial firm and socially desirable. This is in contrast with almost all the previous literature on R&D organization,[19] which shows that private incentives are sufficient on their own to induce duopolistic firms to cooperate over R&D. In this last context, the only case where government intervention is needed is the case where R&D competition yields a higher welfare but smaller profits for the duopoly than R&D cooperation.

3.1.2. Case 2: $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$

The result of the comparison of R&D cooperation and R&D competition, $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$, based on the eco-industry's profit and social welfare is recorded in lemma 2 below.

Lemma 2. *For $\omega_{\max} = 1$, $\omega_{\min} = \omega \in [0,1]$, and $d \in]3,\alpha[$,*

1. $\pi_1^{CS^*} > \pi_1^{NS^*}$;
2. $W^{CS^*} > W^{NS^*}$;
3. *There exist $d_{\pi_2} \in]3,\alpha[$ and $\omega_{\pi_2} \in]0.63,1]$, such that $\pi_2^{CS^*} < \pi_2^{NS^*}$ ($\pi_2^{CS^*} > \pi_2^{NS^*}$) if one of the following holds: (i) $\omega > \omega_{\pi_2}$ ($\omega < 0.63$), (ii) $0.63 < \omega < \omega_{\pi_2}$ and $d < d_{\pi_2}$ ($0.63 < \omega < \omega_{\pi_2}$ and $d > d_{\pi_2}$).*

[19] See, e.g., d'Aspremont and Jacquemin (1988), Kamien et al. (1992). In these papers, however, firms that conduct R&D compete a la Cournot in the final good market. In a different setting from ours, Amir and Wooders (1998) also find that total profits can be higher with R&D competition than with R&D cooperation due to cost asymmetry in the R&D competition case.

Proof. See Appendix C.

Lemma 2 states that the leader eco-industrial firm's profit and social welfare are always larger under R&D cooperation than under R&D competition for $\omega_{\max} = 1$, $\omega_{\min} = \omega \in [0,1]$, and $d \in]3, \alpha[$. However, the follower eco-industrial firm's profit may be larger under R&D competition than under R&D cooperation, depending on the level of marginal damage and the degree of R&D spillovers. Figure 2 above illustrates our findings in Lemma 2 in the (ω, d) space (for $\omega \in [0,1]$, and $d \in]3, \alpha[$).[20] The curve in the figure represents the pairs (ω, d) for which $\Delta\pi_2 = \pi_2^{CS*} - \pi_2^{NS*} = 0$. The pairs of (ω, d) lying on the left (right) side of the curve characterize cases where R&D cooperation induces more (less) profit for the follower eco-industrial firm than R&D competition. The figure shows that R&D cooperation is always desirable (undesirable) from the follower eco-industrial firm standpoint when the level of R&D spillovers ω is below 0.63 (above 0.69). For R&D spillovers between 0.63 and 0.69, R&D cooperation is desirable (undesirable) when the marginal damage is above (below) some specific threshold, which is decreasing as the level of R&D spillovers decreases.

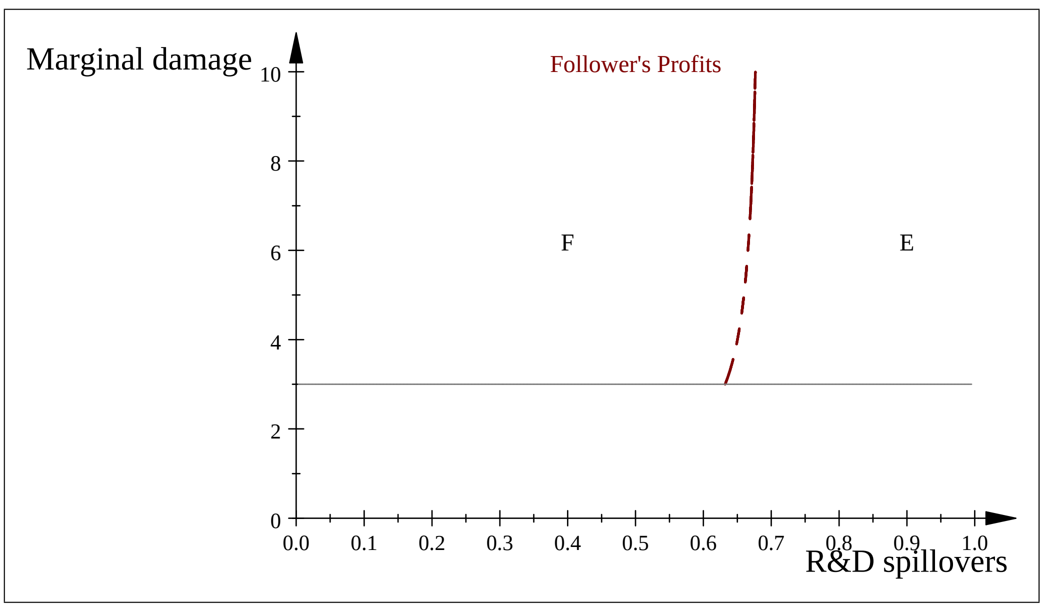

Fig. 2. Follower's profitability when $\omega_{\max}= 1$, $\omega_{\min}= \omega \in [0,1]$, and $\alpha = 10$.

[20] Recall that $\alpha = 10$ for the graphical analysis.

The curve in Figure 2 divides the space of (ω, d) into two disjoint regions - E, and F. Table 2 below provides the specific rankings of the R&D regimes, based on the profits of the eco-industry and social welfare, in each of these two regions.

Table 2 - Ranking of the R&D Regimes according to eco-industry profitability and social welfare when $\omega_{\max}= 1$, $\omega_{\min}= \omega \in [0, 1]$, and $\alpha = 10$

Region E	Region F
$\pi_1^{CS*} > \pi_1^{NS*}$	$\pi_1^{CS*} > \pi_1^{NS*}$
$\pi_2^{CS*} < \pi_2^{NS*}$	$\pi_2^{CS*} > \pi_2^{NS*}$
$W^{CS*} > W^{NS*}$	$W^{CS*} > W^{NS*}$

It is obvious from Table 2 that there is room for government intervention in region E, where the follower eco-industrial firm would prefer R&D competition while a regulator maximizing social welfare would prefer R&D cooperation. Proposition 2 points out the kind of policy that is needed.

Proposition 2. *Suppose that eco-industrial firms that engage in Stackelberg competition in the market for AGS fully share information under R&D cooperation ($\omega_{\max} = 1$). When a government intervention is needed, it is always to induce the follower eco-industrial firm to cooperate over R&D.*

Interestingly, in the case at hand where $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0, 1]$, the level of R&D spillovers under R&D competition ω can be interpreted as the degree of enforcement of intellectual property rights. In this case, a change in ω can clearly originate from a policy intervention: a decrease in ω can result from a stricter enforcement of intellectual property rights. Therefore, from any equilibrium in region E with conflicting preferences between the follower eco-industrial firm and society, the government can induce R&D cooperation, following Proposition 2, by strengthening intellectual property rights. The ensuing decrease in the degree of R&D spillovers will work to move the equilibrium from region E towards region F.

In the next section, we examine R&D efforts and abatement activities.

3.2. R&D efforts and abatement activities

3.2.1. Case 1: $\omega_{\max} = \omega \in [0, 1]$ and $\omega_{\min} = 0$

The following lemma summarizes the main insights from the comparison of equilibrium levels of total R&D efforts, total abatement activities, and net emissions under R&D cooperation versus R&D competition, when $\omega_{\max} = \omega \in [0, 1]$ and $\omega_{\min} = 0$.

Lemma 3. *For $\omega_{\max} = \omega \in [0, 1]$, $\omega_{\min} = 0$, and $d \in]3, \alpha[$,*

1. *$Y^{CS^*} < Y^{NS^*}$;*
2. *There exist $d_A \in]3, \alpha[$ and $\omega_A \in [0, 0.58]$ such that $A^{CS^*} < A^{NS^*}$ and $e^{CS^*} > e^{NS^*}$ ($A^{CS^*} > A^{NS^*}$ and $e^{CS^*} < e^{NS^*}$) if one of the following holds: (i) $\omega < \omega_A$ ($\omega > 0.58$), or (ii) $\omega_A < \omega < 0.58$ and $d < d_A$ ($\omega_A < \omega < 0.58$ and $d > d_A$).*

Proof. See Appendix D.

Lemma 3 suggests that R&D efforts are always higher under R&D competition than under R&D cooperation for $\omega_{\max} = \omega \in [0, 1]$, $\omega_{\min} = 0$, and $d \in]3, \alpha[$. However, abatement activities as well as net emissions levels may be larger or lower depending on the level of the marginal damage and the degree of R&D spillovers. Figure 3 below illustrates our findings in Lemma 3 in the $\omega \times d$ space (for $\omega \in [0, 1]$, and $d \in]3, \alpha[$).[21] The curve in Figure 3 represents the pairs (ω, d) for which $\Delta A = A^{CS^*} - A^{NS^*} = 0$. The pairs of (ω, d) lying on the right (left) side of the curve $\Delta A = 0$ characterize cases where R&D cooperation gives rise to more (less) AGS production, and thus to less (more) pollution, than R&D competition.

[21] Recall that $\alpha = 10$ for the graphical analysis.

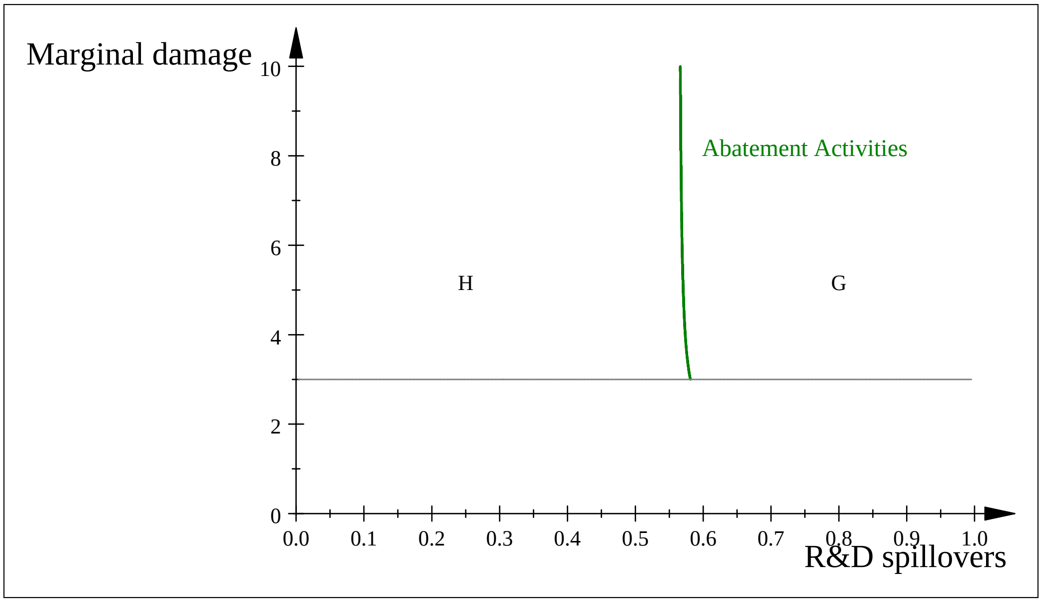

Fig. 3 . Abatement activities when $\omega_{\max}= \omega \in [0,1]$, $\omega_{\min}= 0$, and $\alpha = 10$.

The curve divides Figure 3 in two disjoint regions - denoted by G and H - which correspond to specific rankings of the R&D regimes. Table 3 below characterizes each of the two regions (G and H) according to their corresponding ranking of R&D cooperation and R&D competition in terms of total R&D efforts, abatement activities, and net emissions.

Table 3 - Ranking of the R&D Regimes according to total R&D efforts, total abatement activities, and net emissions when $\omega_{\max}= \omega \in [0,1]$, $\omega_{\min}= 0$, and $\alpha = 10$

Region G	Region H
$Y^{CS^*} < Y^{NS^*}$	$Y^{CS^*} < Y^{NS^*}$
$A^{CS^*} > A^{NS^*}$	$A^{CS^*} < A^{NS^*}$
$e^{CS^*} < e^{NS^*}$	$e^{CS^*} > e^{NS^*}$

This table confirms that R&D competition always results in larger total R&D efforts than R&D cooperation. In turn, R&D cooperation results in larger total abatement activities than R&D competition in regions G, where spillovers are above a certain threshold which is decreasing in the marginal damage. Interestingly, in region G, R&D cooperation always yields more abatement activities than R&D competition while the opposite is true for total R&D efforts. This divergence occurs because R&D competition can give rise to more R&D efforts even when R&D spillovers are significantly large. Indeed, it should be emphasized that R&D competition induces more R&D investments even for maximal R&D spillovers, i.e. $\omega = 1$. This finding contrasts with existing results in the literature on R&D organization which predicts that in the presence of sufficiently large R&D spillovers, duopolists cooperating in R&D but not in output will both spend more on R&D and produce more output than firms competing at both stages [see e.g., d'Aspremont and Jacquemin (1988, 1990)].

An important point to be noticed from Lemma 3 is thus that more R&D efforts result from R&D competition than from R&D cooperation if $\omega_{\max} = \omega \in [0, 1]$, $\omega_{\min} = 0$, and the marginal damage is sufficiently high ($d > 3$), even when R&D spillovers are significantly high, but this does not translate into more AGS production under R&D competition than under R&D cooperation. This result can be explained by the strategic behavior inherent in upstream environmental R&D. In fact, large marginal environmental damages induce more stringent emission taxes, which increase the market power that the eco-industry enjoys as the demand for AGS becomes more inelastic. As a consequence, eco-industrial firms that engage in R&D competition are now trying to become the sole beneficiaries of any surplus of investments in cost-reducing R&D by increasing their markups instead of increasing their output. As noted above, this can be detrimental to the quality of the environment and social welfare. We highlight this result in our third proposition.

Proposition 3. *Suppose that there are no involuntary information leakages ($\omega_{\min} = 0$) under R&D competition between eco-industrial firms that engage in Stackelberg competition in the market for AGS. For sufficiently large marginal environmental damages ($d > 3$), R&D competition in the eco-industry always induce more total R&D efforts than R&D cooperation, even when R&D spillovers are maximal ($\omega = 1$). However, the ensuing excess R&D efforts does not necessarily translate into more abatement activities and a larger social welfare: we can have $Y^{NS^*} > Y^{CS^*}$, $A^{NC^*} < A^{CS^*}$, and $W^{NC^*} < W^{CS^*}$.*

It may appear intuitive that the government could increase environmental R&D activities by encouraging environmental R&D competition through the establishment of a well functioning patent system.[22] Proposition 3 suggests that this innovation policy should be coupled with specific injunctions to ensure that the amount of R&D efforts in the eco-industry will truly translate into a larger and more affordable supply of abatement goods and services to polluters. In particular, because the extra amount of R&D efforts that may be generated under R&D competition (in comparison to R&D cooperation) does not necessarily result in better quality for the environment and more social welfare, regulatory authorities should not rely on the total level of environmental R&D expenditures in the eco-industry as a target variable for environmental innovation policy.

Another divergence in the ranking of R&D cooperation and R&D competition is worth highlighting. Even when total R&D efforts and abatement activities induce the same ranking of the R&D regimes, this ranking does not necessarily apply to comparisons involving social welfare. For example, by combining Figure 1 and Figure 3, it is straightforward to see that part of region H in Figure 3, where $Y^{CS^*} < Y^{NS^*}$ and $A^{CS^*} < A^{NS^*}$, is included in regions A and B altogether, where $W^{CS^*} > W^{NS^*}$. This departs from the results in Poyago-Theotoky (2007) who finds the same ranking for the two R&D regimes based on R&D efforts and social welfare. All this is quite intuitive. R&D cooperation achieves a gain in efficiency to produce a given amount of AGS. Therefore, even if abatement activities decrease following R&D cooperation, social welfare may still increase thanks to the savings on R&D related costs. However, this is the case only if the level of R&D spillovers ω is large enough. Otherwise, R&D cooperation will result in a loss of welfare because of the decrease in abatement activities, which itself is a result of the increased market power of the eco-industrial firms stemming from their cooperation over R&D. The policy message that this observation conveys is that maximizing abatement activities should not

[22] For example, Canada and the US have been offering for the last few years expedited processing for green technology patent applications. For more information on these programs, see http://www.cipo.ic.gc.ca/eic/site/cipointernet-internetopic.nsf/eng/wr02462.html and http://www.uspto.gov/patents/init_events/green_tech.jsp (accessed on January 31, 2013).

be considered either as the ultimate goal of environmental innovation policies.

3.2.2. Case 2: $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0, 1]$

The following lemma summarizes the main insights from the comparison of equilibrium levels of total R&D efforts, total abatement activities, and net emissions under R&D cooperation versus R&D competition, when $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0, 1]$.

Lemma 4. *For $\omega_{\max} = 1$, $\omega_{\min} = \omega \in [0, 1]$, and $d \in]3, \alpha[$,*

1. $A^{CS^*} > A^{NS^*}$ *and* $e^{CS^*} < e^{NS^*}$;
2. *There exists $d_Y \in]3, \alpha[$ and $\omega_Y \in [0, 1]$ such that $Y^{CS^*} > Y^{NS^*}$ ($Y^{CS^*} < Y^{NS^*}$) if one of the following holds: (i) $\omega > \omega_Y$, or (ii) $0 < \omega < \omega_Y$ and $d < d_Y$ ($0 < \omega < \omega_Y$ and $d > d_Y$).*

Proof. See Appendix E.

Lemma 4 states that R&D cooperation always results in more total abatement activities (and thus less net emissions) than R&D competition for $\omega_{\max} = 1$, $\omega_{\min} = \omega \in [0, 1]$, and $d \in]3, \alpha[$. However, R&D efforts may be higher under R&D competition than under R&D cooperation depending on the level of the marginal damage and the degree of R&D spillovers. Figure 4 below illustrates our findings in Lemma 4 in the $\omega \times d$ space (for $\omega \in [0, 1]$, and $d \in]3, \alpha[$).[23] The curve in Figure 4 represents the pairs (ω, d) for which $\Delta Y = Y^{CS^*} - Y^{NS^*} = 0$.

[23] Recall that $\alpha = 10$ for the graphical analysis.

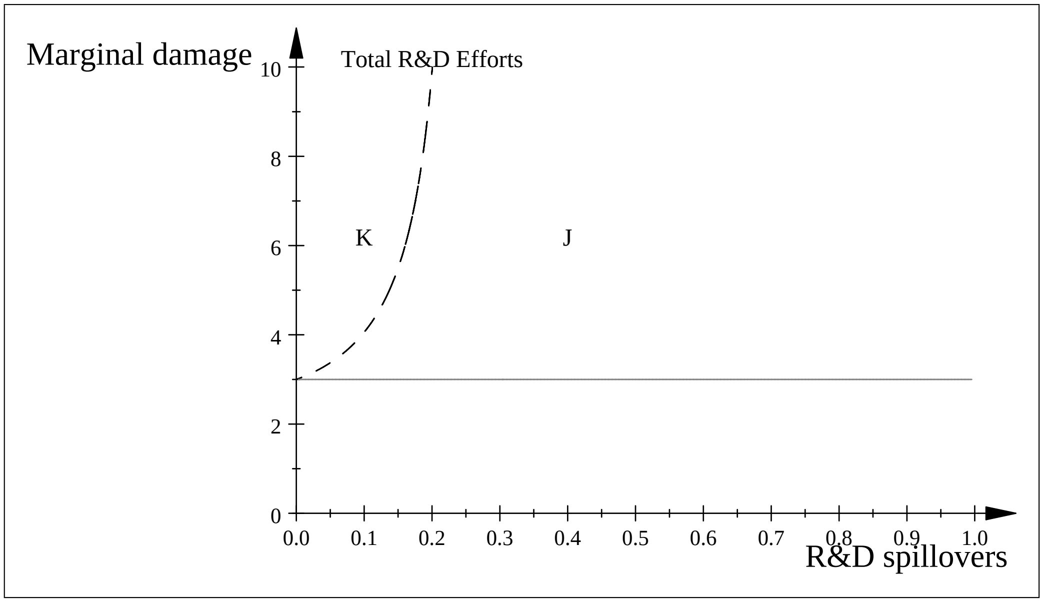

Fig. 4. Total R&D efforts when $\omega_{\max}= 1$, $\omega_{\min}= \omega \in [0, 1]$, and $\alpha = 10$.

The curve divides the figure in two disjoint regions - denoted by J and K. Table 4 below characterizes each one of regions J and K according to their corresponding ranking of R&D cooperation and R&D competition in terms of total R&D efforts, abatement activities, and net emissions.

Table 4 - Ranking of the R&D Regimes according to total R&D efforts, total abatement activities, and net emissions when $\omega_{\max}= 1$, $\omega_{\min}= \omega \in [0, 1]$, and $\alpha = 10$.

Region J	Region K
$Y^{CS^*} > Y^{NS^*}$	$Y^{CS^*} < Y^{NS^*}$
$A^{CS^*} > A^{NS^*}$	$A^{CS^*} > A^{NS^*}$
$e^{CS^*} < e^{NS^*}$	$e^{CS^*} < e^{NS^*}$

Table 4 confirms that R&D cooperation always results in more abatement efforts (and thus less net emissions) than R&D competition. Again, for some values of ω and d, a divergence occurs between the ranking of the R&D regimes based on R&D efforts and abatement activities. Indeed, in region K, R&D competition in the eco-industry induces more total R&D efforts than R&D cooperation. However, the extra R&D efforts under

R&D competition do not translate into more abatement activities and/or a larger social welfare: we have $Y^{CS^*} < Y^{NS^*}$ and $A^{CS^*} > A^{NS^*}$ and $W^{CS^*} > W^{NS^*}$.

4. Concluding remarks

The recent evolution of environmental regulations has drastically changed the economics of abatement activities. To comply with more stringent regulations, polluting firms increasingly rely on a specialized eco-industry for innovative and masterminded abatement solutions. In such a context where environmental R&D and abatement activities are outsourced to the upstream eco-industry, it remains important to ask a key question: how does environmental R&D cooperation rank compared to environmental R&D competition with respect to total R&D efforts, total abatement activities, the quality of the environment, and social welfare?

Our analysis brings in three main insights about the organization of environmental R&D. First, we showed that both the level of the marginal damage from pollution and the degree of R&D spillovers play a role in the welfare ranking of R&D cooperation and R&D competition. The intuition for the role of the marginal damage is that its level determines the stringency level of environmental regulations, which in turn determines the extent of the market power of the eco-industry. Second, we determined that government intervention might be necessary for R&D cooperation to occur, in the context of our model. In the case with full information sharing under R&D cooperation and involuntary information leakages under R&D competition, we established that government intervention in the organization of environmental R&D might be warranted, for example by increasing the enforcement of intellectual property rights to induce the follower eco-industrial firm to cooperate over R&D. Last, we showed that in the presence of an eco-industry, more environmental R&D efforts do not necessarily correspond to more abatement activities, less net emissions, and more social welfare. In the case when there are no involuntary leakages under R&D competition, this last result occurs due to the fact that R&D competition can give rise to more R&D efforts even when R&D spillovers are significantly large, whenever the marginal environmental damage is relatively high.

The results derived in this paper have interesting ramifications for environmental R&D policy. As noted above, government interventions may be needed to enhance R&D cooperation in the eco-industry. The interactive effect of the level of marginal environmental damage and the degree of R&D spillovers on the eco-industry's behavior are important in the choice of the suitable innovation policy. Also, it appears that the government should exercise caution in determining the ultimate target for environmental R&D policy. Specifically, because more R&D efforts under R&D competition does not necessarily guarantee a better quality for the environment and that a larger social welfare will be achieved, regulatory authorities should not rely only on the total level of environmental R&D expenditures in the eco-industry and/or the total amount of abatement activities as a target variable for environmental innovation policy.

Finally, one should note that some interesting dimensions of the organization of environmental R&D have not been addressed by our analysis. In particular, we considered that the emission tax is fixed at the Pigouvian level. Although, this assumption is realistic in the context of our analysis, an interesting extension would be to consider a case where the regulator chooses an optimal emission tax that takes into account the different sources of market failures.[24] Also, we could consider the level of R&D spillovers as an endogenous variable. Further, the analysis of a more general case where the sharing of R&D costs can be asymmetric would be interesting. We leave these extensions for future research.

[24] We are grateful to an anonymous referee for this suggestion.

Appendices

A: Equilibria of the R&D cooperation and competition cases

The following equilibrium obtains for our game in the R&D cooperation case:

$$\begin{aligned}
y^{CS*} &= \frac{3(1+\omega)(t\xi-g)}{16t-3(\omega+1)^2} \\
Y^{CS*} &= \frac{6(1+\omega)(t\xi-g)}{16t-3(\omega+1)^2} \\
a_1^{CS*} &= \frac{8(t\xi-g)}{16t-3(\omega+1)^2} \\
a_2^{CS*} &= \frac{4(t\xi-g)}{16t-3(\omega+1)^2} \\
A^{CS*} &= \frac{12(t\xi-g)}{16t-3(\omega+1)^2} \\
\pi_1^{CS*} &= \frac{(t\xi-g)^2\left[64t-9(\omega+1)^2\right]}{2\left[16t-3(\omega+1)^2\right]^2} \\
\pi_2^{CS*} &= \frac{(t\xi-g)^2\left[32t-9(\omega+1)^2\right]}{2\left[16t-3(\omega+1)^2\right]^2} \\
x^{CS*} &= \alpha-t \\
e^{CS*} &= Max\left\{0, \alpha-t-12\left[\frac{\xi(t\xi-g)}{16t-3(\omega+1)^2}-\frac{6(t\xi-g)^2}{\left(16t-3(\omega+1)^2\right)^2}\right]\right\}.
\end{aligned} \tag{A.1}$$

In turn, the equilibrium of our game in the R&D competition case is given by:

$$
\begin{aligned}
y_1^{NC^*} &= \frac{4(2-\omega)\left[(2t-3)+\omega(5-2\omega)\right](t\xi-g)}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \\
y_2^{NC^*} &= \frac{4(3-2\omega)\left[(t-2)+\omega(3-\omega)\right](t\xi-g)}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \\
Y^{NC^*} &= \frac{4\left[(7-4\omega)(t-2)+2\omega(2\omega-3)(\omega-3)+2\right](t\xi-g)}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \\
a_1^{NC^*} &= \frac{8(t\xi-g)\left[2t-(\omega-1)(2\omega-3)\right]}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \\
a_2^{NC^*} &= \frac{8(t\xi-g)\left[t-(\omega-1)(\omega-2)\right]}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \qquad \text{(A-2)} \\
A^{NC^*} &= \frac{8(t\xi-g)\left[3t-(\omega-1)(3\omega-5)\right]}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)} \\
\pi_1^{NC^*} &= \frac{8(t\xi-g)^2\left[2t-(\omega-1)(2\omega-3)\right]^2\left[4t-(\omega-2)^2\right]}{\left\{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2} \\
\pi_2^{NC^*} &= \frac{8(t\xi-g)^2\left[t-(\omega-1)(\omega-2)\right]^2\left[8t-(2\omega-3)^2\right]}{\left\{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2} \\
x^{NS^*} &= \alpha-t \\
e^{NS^*} &= Max\left\{\begin{array}{l} 0, \alpha-t-\left[\frac{8\xi(t\xi-g)[3t-(\omega-1)(3\omega-5)]}{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)}\right. \\ \qquad \left. -\frac{32(t\xi-g)^2[3t-(\omega-1)(3\omega-5)]^2}{\left\{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2}\right] \end{array}\right\}.
\end{aligned}
$$

Substituting (A.1) into (16) and after some manipulations, we find the following expression of the equilibrium level of social welfare under R&D cooperation:

$$
W^{CS^*} = \frac{(\alpha-d)^2}{2} + \frac{\left[120d-9(1+\omega)^2\right](d\xi-g)^2}{\left[16d-3(\omega+1)^2\right]^2}. \qquad \text{(A.3)}
$$

Similarly, we obtain the expression of the equilibrium level of social welfare under R&D competition by substituting the equilibrium levels of polluting output, abatement, and R&D efforts, as given in (A.2), into (16).

B: Proof of Lemma 1

First, recall that $t = d$ by assumption. When $\omega_{\max} = \omega \in [0, 1]$ and $\omega_{\min} = 0$, we get from (A.1) and (A.2) the following expressions of the variation of the profits of the leader and follower eco-industrial firms, respectively.

$$\pi_1^{CS*} - \pi_1^{NS*} = \frac{(d\xi - g)^2 \left\{ \left[64d - 9(\omega+1)^2\right] \left[(8d-9)(d-1) - 3\right]^2 - 4\left[16d - 3(\omega+1)^2\right]^2 (d-1)(2d-3)^2 \right\}}{2\left[16d - 3(\omega+1)^2\right]^2 \left[(8d-9)(d-1)-3\right]^2}$$

$$\pi_2^{CS*} - \pi_2^{NS*} = \frac{(d\xi - g)^2 \left\{ \left[32d - 9(1+\omega)^2\right] \left[(8d-9)(d-1) - 3\right]^2 - \left[16d - 3(\omega+1)^2\right]^2 (d-2)^2 (8d-9) \right\}}{2\left[16d - 3(\omega+1)^2\right]^2 \left[(8d-9)(d-1)-3\right]^2}.$$

Based on our assumptions, the sign of $\pi_1^{CS*} - \pi_1^{NS*}$ is given by the sign of

$$\left[64d - 9(\omega+1)^2\right] \left[(8d-9)(d-1) - 3\right]^2 - 4\left[16d - 3(\omega+1)^2\right]^2 (d-1)(2d-3)^2.$$

For $\omega \in [0, 1]$ and $d \in]3, \alpha[$, the graphical analysis in Figure 1 and simple calculus based on the latter expression reveal that $\pi_1^{CS*} - \pi_1^{NS*} < 0$, when: (i) $\omega < \omega_{\pi_1}$, where ω_{π_1} depends on the value of α; or (ii) $\omega_{\pi_1} < \omega < 0.42$ and d is sufficiently low. The opposite holds, i.e. $\pi_1^{CS*} - \pi_1^{NS*} > 0$, when: (i) $\omega > 0.42$, or (ii) $\omega_{\pi_1} < \omega < 0.42$ and d is sufficiently large.

The sign of $\pi_2^{CS*} - \pi_2^{NS*}$ is in turn given by the sign of

$$\left[32d - 9(1+\omega)^2\right] \left[(8d-9)(d-1) - 3\right]^2 - \left[16d - 3(\omega+1)^2\right]^2 (d-2)^2 (8d-9),$$

which can be shown to be always positive for $\omega \in [0, 1]$ and $d \in]3, \alpha[$, using simple calculus and graphical analysis.

Finally, the expressions of the equilibrium levels of social welfare can be used to compute the following expression for $\omega_{\max} = \omega \in [0, 1]$ and $\omega_{\min} = 0$,

$W^{CS^*} - W^{NS^*} =$

$$\frac{(d\xi - g)^2 \left\{ \left[120d - 9(\omega+1)^2\right] \left[(8d-9)(d-1)-3\right]^2 - \left(30d^3 - \frac{225}{2}d^2 + 126d - 36\right) \left[16d - 3(\omega+1)^2\right]^2 \right\}}{\left[16d - 3(\omega+1)^2\right]^2 \left[(8d-9)(d-1)-3\right]^2}.$$

The sign of $W^{CS^*} - W^{NS^*}$ is given by the sign of

$$\left[120d - 9(\omega+1)^2\right] \left[(8d-9)(d-1)-3\right]^2 - \left(30d^3 - \frac{225}{2}d^2 + 126d - 36\right) \left[16d - 3(\omega+1)^2\right]^2.$$

For $\omega \in [0,1]$ and $d \in]3, \alpha[$, we can show that on the one hand, $W^{CS^*} - W^{NS^*} < 0$ when: (i) $\omega < \omega_W$, where ω_W depends on the value of α; or (ii) $\omega_W < \omega < 0.37$ and d is sufficiently low. On the another hand, $W^{CS^*} - W^{NS^*} > 0$ when: (i) $\omega > 0.37$; or (ii) $\omega_W < \omega < 0.37$ and d is sufficiently large. ■

C: Proof of Lemma 2

First, recall that $t = d$ by assumption. When $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$,and based on our assumptions, the sign of $\pi_1^{CS^*} - \pi_1^{NS^*}$ is given by the sign of

$$(16t-9)\left\{\left[4t - (\omega-2)^2\right]\left[8t - (2\omega-3)^2\right] - (\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2 \\ - 64(4t-3)^2\left[2t - (\omega-1)(2\omega-3)\right]^2\left[4t - (\omega-2)^2\right],$$

which can be shown to be always positive for $\omega \in [0,1]$ and $d \in]3, \alpha[$, using simple calculus and graphical analysis. The sign of $\pi_2^{CS^*} - \pi_2^{NS^*}$ is in turn given by the sign of

$$(8t-9)\left\{\left[4t - (\omega-2)^2\right]\left[8t - (2\omega-3)^2\right] - (\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2 \\ - 64(4t-3)^2\left[t - (\omega-1)(\omega-2)\right]^2\left[8t - (2\omega-3)^2\right].$$

For $\omega \in [0,1]$ and $d \in]3, \alpha[$, the graphical analysis in Figure 2 and simple calculus based on the latter expression reveal that $\pi_2^{CS^*} - \pi_2^{NS^*} < 0$, when: (i) $\omega > \omega_{\pi_2}$, where ω_{π_2} depends on the value of α; or (ii) $0.63 < \omega < \omega_{\pi_2}$ and d is sufficiently low. The opposite holds, i.e. $\pi_2^{CS^*} - \pi_2^{NS^*} > 0$, when: (i) $\omega < 0.63$, or (ii) $0.63 < \omega < \omega_{\pi_2}$ and d is sufficiently large.

Finally, the sign of $W^{CS^*} - W^{NS^*}$ for $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$ is given by the sign of

$$
\begin{aligned}
&(30d-9)\left\{\left[4d-(\omega-2)^2\right]\left[8d-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}^2 \\
&\quad -32(4d-3)^2(2-\omega)\left[d(4+6\omega)+(1-\omega)\left(6\omega^2-7\omega-6\right)\right]\left[(2d-3)+\omega(5-2\omega)\right] \\
&\quad -32(4d-3)^2(3-2\omega)\left[d(1+10\omega)+(1-\omega)\left(10\omega^2-15\omega-2\right)\right]\left[(d-2)+\omega(3-\omega)\right] \\
&-128(4d-3)^2\left\{\left[5d-3(\omega-2)^2\right]d-(\omega-1)(\omega-2)(2\omega-3)(\omega+1)\right\}\left[3d-(\omega-1)(3\omega-5)\right],
\end{aligned}
$$

which can be shown to be always positive for $\omega \in [0,1]$ and $d \in]3,\alpha[$, using simple calculus and graphical analysis. ■

D: Proof of Lemma 3

First, recall that $t = d$ by assumption. When $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$, subtracting the expressions of the equilibrium levels of total R&D efforts in (A.1) and (A.2) yields:

$$
Y^{CS^*} - Y^{NS^*} = \frac{(d\xi - g)\left\{6(1+\omega)\left[(8d-9)(d-1)-3\right]-(7d-12)\left[16d-3(\omega+1)^2\right]\right\}}{\left[16d-3(\omega+1)^2\right]\left[(8d-9)(d-1)-3\right]}.
$$

Given our assumptions, the sign of $Y^{CS^*} - Y^{NS^*}$ corresponds to the sign of

$$
6(1+\omega)\left[(8d-9)(d-1)-3\right]-(7d-12)\left[16d-3(\omega+1)^2\right].
$$

For $\omega \in [0,1]$ and $d \in]3,\alpha[$, we can use the graphical analysis in Figure 3 and simple calculus to show that $Y^{CS^*} < Y^{NS^*}$.

From the equilibrium levels of total abatement activities in (A.1) and (A.2), when $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$, we can get

$$
A^{CS^*} - A^{NS^*} = \frac{2(d\xi - g)\left\{6\left[(8d-9)(d-1)-3\right]-(3d-5)\left[16d-3(\omega+1)^2\right]\right\}}{\left[16d-3(\omega+1)^2\right]\left[(8d-9)(d-1)-3\right]}.
$$

The sign of $A^{CS^*} - A^{NS^*}$ corresponds to the sign of

$$6\left[(8d-9)(d-1)-3\right]-(3d-5)\left[16d-3(\omega+1)^2\right].$$

For $\omega \in [0,1]$ and $d \in \left]3,\alpha\right[$, we can check that, on one hand, $A^{CS^*} < A^{NS^*}$ when: (i) $\omega < \omega_A$, where ω_A depends on the value of α; or (ii) $\omega_A < \omega < 0.58$ and d is sufficiently low. On another hand, $A^{CS^*} > A^{NS^*}$ when: (i) $\omega > 0.58$; or (ii) $\omega_A < \omega < 0.58$ and d is sufficiently large.

Finally, subtracting the expressions of the equilibrium levels of net emissions in (A.1) and (A.2) when $\omega_{\max} = \omega \in [0,1]$ and $\omega_{\min} = 0$ gives rise to

$$e^{CS^*}-e^{NS^*}=$$
$$\frac{1}{2}\left[\frac{12(d\xi-g)}{16d-3(\omega+1)^2}-\frac{2(3d-5)(d\xi-g)}{(8d-9)(d-1)-3}\right]\left[\frac{12(d\xi-g)}{16d-3(\omega+1)^2}+\frac{2(3d-5)(d\xi-g)}{(8d-9)(d-1)-3}-2\xi\right],$$

which can also be written as

$$e^{CS^*}-e^{NS^*}=\frac{1}{2}\left(A^{CS^*}-A^{NS^*}\right)\left(A^{CS^*}+A^{NS^*}-2\xi\right).$$

Since $\xi > A^{CS^*}$ and $\xi > A^{NS^*}$ from our assumptions, it is straightforward that $A^{CS^*} + A^{NS^*} - 2\xi < 0$. Therefore, $e^{CS^*} - e^{NS^*}$ and $A^{CS^*} - A^{NS^*}$ always have opposite signs. ■

E: Proof of Lemma 4

First, recall that $t = d$ by assumption. When $\omega_{\max} = 1$ and $\omega_{\min} = \omega \in [0,1]$, and given our assumptions, the sign of $Y^{CS^*} - Y^{NS^*}$ corresponds to the sign of

$$3\left\{\left[4t-(\omega-2)^2\right]\left[8t-(2\omega-3)^2\right]-(\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\}$$
$$-4(4t-3)\left[(7-4\omega)(t-2)+2\omega(2\omega-3)(\omega-3)+2\right].$$

For $\omega \in [0,1]$ and $d \in \left]3,\alpha\right[$, we can use the graphical analysis in Figure 4 and simple calculus to show that, on one hand, $Y^{CS^*} > Y^{NS^*}$ when: (i) $\omega > \omega_Y$, where ω_Y depends on the value of α; or $0 < \omega < \omega_Y$ and d is sufficiently low. On another hand, $Y^{CS^*} < Y^{NS^*}$ when $0 < \omega < \omega_Y$ and d is sufficiently large.

From the equilibrium levels of total abatement activities in (A.1) and (A.2), when $\omega_{\max} = 1$, $\omega_{\min} = \omega \in [0,1]$, the sign of $A^{CS^*} - A^{NS^*}$ corresponds to the sign of

$$3\left\{\left[4t - (\omega-2)^2\right]\left[8t - (2\omega-3)^2\right] - (\omega-2)(3\omega-2)(2\omega-1)(2\omega-3)\right\} \\ - 8(4t-3)\left[3t - (\omega-1)(3\omega-5)\right].$$

For $\omega \in [0,1]$ and $d \in]3, \alpha[$, we can check that $A^{CS^*} > A^{NS^*}$. Finally, it is direct to show that $e^{CS^*} - e^{NS^*}$ and $A^{CS^*} - A^{NS^*}$ always have opposite signs (see Proof of Lemma 3 above). ■

References

[1] Amir R., and J. Wooders (1998), "Cooperation vs. Competition in R&D: The Role of Stability of Equilibrium", *Journal of Economics*, 67(1), 63-73.

[2] Amir, M., Amir, R., and J. Jin (2000), "Sequencing R&D Decisions in a Two-Period Duopoly with Spillovers", *Economic Theory*, 15, 297-317.

[3] Amir, R., Nannerup, N., Stepanova, A., and E. Eguiazarova (2002), "Monopoly versus R&D-Integrated Duopoly", *The Manchester School*, 70(1), 88-100.

[4] Atallah, G. (2002), "Vertical R&D Spillovers, Cooperation, Market Structure, and Innovation", *Economics of Innovation and New Technology*, 16(7), 559-86.

[5] ——— (2007), "Research Joint Ventures with Asymmetric Spillovers and Symmetric Contributions", *Economics of Innovation and New Technology*, 11(3), 179-209.

[6] Banerjee, S. and P. Lin (2001), "Vertical Research Joint Ventures", *International Journal of Industrial Organization*, 19(1): 285-302.

[7] ——— (2003), "Downstream R&D, Raising Rivals' Costs, and Input Price Contracts", *International Journal of Industrial Organization*, 21(1): 79-96.

[8] Baumol, W.J. (1995), "Environmental Industries with Substantial Start-Up Costs as Contributors to Trade Competitiveness", *Annual Review of Energy and Environment*, 20: 71-81.

[9] Biglaiser, G. and J.K. Horowitz (1995), "Pollution Regulation and Incentives for Pollution-Control Research", *Journal of Economics and Management Strategy*, 3: 663-684.

[10] Brander, J.A. and B.J. Spencer (1983), "Strategic Commitment with R&D: the Symmetric Case", *Bell Journal of Economics*, 14: 225-35.

[11] Brocas, I. (2003), "Vertical Integration and Incentives to Innovate", *International Journal of Industrial Organization*, 21(4): 457-88.

[12] Canton, J., Soubeyran, A. and H. Stahn (2008), "Optimal Environmental Policy, Vertical Structure and Imperfect Competition", *Environmental and Resource Economics*, 40: 369-382.

[13] Chen, Y. and D.E.M. Sappington (2010), "Innovation in Vertically Related Markets", *Journal of Industrial Economics*, 58(2): 373-401.

[14] Chiou, J.R. and J.L. Hu (2001), "Environmental Research Joint Ventures under Emission Taxes", *Environmental and Resource Economics*, 21: 129-146.

[15] d'Aspremont, C. and A. Jacquemin (1988), "Cooperative and Noncooperative R&D with Spillovers", *American Economic Review*, 78(3): 641-42.

[16] ——— (1990), "Cooperative and Noncooperative R&D with Spillovers: Erratum", *American Economic Review*, 80(5): 1133-37.

[17] David, M. and B. Sinclair-Desgagné (2005), "Environmental Regulation and the Eco-Industry", *Journal of Regulatory Economics*, 28(2): 141-55.

[18] ——— (2010), "Pollution Abatement Subsidies and the Eco-Industry", *Environmental and Resource Economics*, 45(2): 271-82.

[19] David, M., Nimubona A-D., and B. Sinclair-Desgagné (2011), "Emission Taxes and the Market for Abatement Goods and Services", *Resource and Energy Economics*, 33(1): 179-91.

[20] Denicolo, V. (1999), "Pollution-Reducing Innovations under Taxes or Permits", *Oxford Economic Paper*s, 51: 184-99.

[21] Environmental Business International (2011), *EBI Report 2020: The U.S. Environmental Industry and Global Market*, San Diego.

[22] Feess, E. and G. Muehlheusser (2002), "Strategic Environmental Policy, Clean Technologies, and the Learning Curve", *Environmental and Resource Economics*, 23: 149-66.

[23] Golombek, R., Greaker, M. and M. Noel (2010), "Carbon Taxes and Innovation without Commitment", *The B.E. Journal of Economic Analysis and Policy*, 10(1), article 32.

[24] Greaker, M.(2006), "Spillovers in the Development of New Pollution Abatement Technology: a New Look at the Porter Hypothesis", *Journal of Environmental Economics and Management*, 52: 411-20.

[25] ——— and K.E. Rosendahl (2008), "Environmental Policy with Upstream Pollution Abatement Technology Firms", *Journal of Environmental Economics and Management*, 56(3): 246-59.

[26] Greaker, M. and M. Hoel (2011), "Incentives for Environmental R&D", CESifo Working Paper n°3468.

[27] Hackett, S.C. (1995), "Pollution-Controlling Innovation in Oligopolistic Industries: Some Comparisons between Patent Races and Research Joint Ventures", *Journal of Environmental Economics and Management*, 29: 339-56.

[28] Hanemann, M. (2009), "The Role of Emission Trading in Domestic Climate Policy", *The Energy Journal*, 30: 79-114.

[29] Henriques, I. (1990), "Cooperative and Noncooperative R&D in Duopoly with Spillovers: Comment", *American Economic Review*, 80(3): 683-40.

[30] Heyes, A. and S. Kapur (2011), "Regulatory Attitudes and Environmental Innovation in a Model Combining Internal and External R&D", *Journal of Environmental Economics and Management*, 61: 327-40.

[31] Ishii, A. (2004), "Cooperative R&D between Vertically Related Firms with Spillovers", *International Journal of Industrial Organization*, 22(8-9): 1213-35.

[32] Kamien, M.I., Muller, E., and I. Zang (1992), "Research Joint Ventures and R&D Cartels", *American Economic Review*, 82: 1293-306.

[33] Katsoulacos, Y. and D. Ulph (1998), "Endogenous Spillovers and the Performance of Research Joint Ventures", *Journal of Industrial Economics*, 46: 333-57.

[34] ——— (2001), "The Effects of Environmental Policy on the Performance of Environmental Research Joint Ventures", in *Behavioral and Distributional Effects of Environmental Policy*, Carraro C. and G.E. Metcalf, eds., University of Chicago Press.

[35] Laffont J.-J. and J. Tirole (1996a), "Pollution Permits and Compliance Strategies", *Journal of Public Economics*, 62 (1-2): 85-125.

[36] ——— (1996b), "Pollution Permits and Environmental Innovation", *Journal of Public Economics*, 62 (1-2): 127-40.

[37] Lambertini, L., Lotti, F., and E. Santarelli (2004), "Infra-Industry Spillovers and R&D Cooperation: Theory and Evidence", *Economics of Innovation and New Technology*, 13(4): 311-28.

[38] Lanjouw, J.O. and A. Mody (1996), "Innovation and the International Diffusion of Environmentally Responsive Technology", *Research Policy*, 25(5): 549-71.

[39] Leahy, D. and J.P. Neary (2007), "Absorptive Capacity, R&D Spillovers, and Public Policy", *International Journal of Industrial Organization*, 25: 1089-108.

[40] Liu, J. (2011), *Tradable Permits, Environmental R&D, and Taxation*, Doctoral Dissertation, University of Ottawa, August 2011.

[41] Nimubona, A.D. and B. Sinclair-Desgagné (2013), "The Pigouvian Tax Rule in the Presence of an Eco-Industry", *Economics Bulletin, 33(1): 747-52.*

[42] ——— (2011), "Polluters and Abaters", *Annals of Economics and Statistics*, 103/104: 9-24.

[43] OECD/Eurostat (1999), *The Environmental Goods and Services Industry*, Paris: OECD Publishing.

[44] Parry, W. (1995), "Optimal Pollution Taxes and Endogenous Technological Progress", *Resource and Energy Economics*, 17: 69-85.

[45] Perino, G. (2010), "Technology Diffusion with Market Power in the Upstream Industry", *Environmental and Resource Economics*, 46(4): 403-28.

[46] Poyago-Theotoky, J.A. (1999), "A Note on Endogenous Spillovers in a Non-Tournament R&D Duopoly", *Review of Industrial Organization*, 15: 253-262.

[47] ——— (2007), "The Organization of R&D and Environmental Policy", *Journal of Economic Behavior and Organization*, 62: 63-75.

[48] ——— (2010), "Corrigendum to The Organization of R&D and Environmental Policy", *Journal of Economic Behavior and Organization*, 76: 449.

[49] Sanyal, P. and S. Ghosh (2010), "Product Market Competition and Upstream Innovation: Theory and Evidence from the US Electricity Market Deregulation", Working Paper, Brandeis University.

[50] Scott, J.T. (1996), "Environmental Research Joint Ventures Among Manufacturers", *Review of Industrial Organization*, 11: 655-679.

[51] ——— (2005), "Public Policy and Environmental Research and Development", in Essays in Honor of Edwin Mansfield, Ed. A.N. Link and F.M. Scherer, Springer, 109-127.

[52] Sinclair-Desgagné, B. (2008), "The Environmental Goods and Services Industry", *International Review of Environmental and Resource Economics*, 2(1): 69-99.

[53] Suzumura, K. (1992), "Cooperative and Noncooperative R&D in an Oligopoly with Spillovers", *American Economic Review*, 82(5): 1307-1320.

[54] Taylor, M. (2008), "Induced Technical Innovation under Cap-and-Trade Abatement Programs", Working Paper, Goldman School of Public Policy, University of California, Berkeley.

[55] Versaevel, B. and D. Vencatachellum (2009), "R&D Delegation in a Duopoly with Spillovers", *The B.E. Journal of Economic Analysis and Policy*, 9(1), Article 55.