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Abstract

The present paper uses a setting where firms commit to environmental R&D expenditure that reduces their emission levels before the regulator sets the emission tax. It examines two scenarios with respect to the organization of environmental R&D: (i) independent R&D and (ii) an industry-wide environmental R&D Cartel (ERC). In the first scenario (1) firms choose their emission-reducing R&D non-cooperatively, (2) the regulator sets the emission tax and (3) firms compete in the market by choosing quantities. In the second scenario both the second and third stages remain the same, however, in the first stage firms form an industry-wide ERC that cooperatively undertakes environmental R&D. Thus, in both R&D scenarios, the regulator follows a time-consistent policy; this corresponds to the case where the regulator is unable to commit credibly to the emission tax.

It is shown that for relatively small damages, environmental innovation is higher in the case of an ERC compared to independent R&D, while for relatively large damages the opposite is true. The same ranking applies to the comparison of social welfare. However, firms always have an incentive to be part of an industry-wide ERC as this increases their profitability.

Keywords: Voluntary approaches,environmental innovation, environmental policy, emission taxes, R&D cooperation.

JEL Classification: Q280, O320, H290, D430, L130

1 Introduction

In recent years there has been an increase in the number of voluntary agreements as an environmental policy tool, the majority of these aiming to reduce CO_2 emissions in relation to global warming. The excellent survey by Brau and Carraro (1998) provides a comprehensive review of recent research in the area.

Rational firms, anticipating a government's or regulator's actions - usually in the form of introducing or increasing emission taxation, have an incentive to voluntary reduce their emission levels so that their tax bill gets reduced. (Conrad (1998) and Petrakis and Xepapadeas (1998)). Conrad (1998) considers a strategic trade setting where firms commit to abatement efforts that will reduce the polluting productive input in anticipation of an emission tax set by competing governments. He finds that firms sacrifice profit and reduce production and thus use less of the polluting input and are rewarded by a less strict policy in the form of lower emission taxes (this constitutes a voluntary approach). Petrakis and Xepapadeas (1998) analyze the case of a polluting monopolist who faces a government setting an emission tax, taking into account the dynamic inconsistency problem (a policy is inconsistent in a dynamic sense if an optimal action defined at time t ceases to be optimal at time T ($T > t$) even with no change in the information structure). They show that the optimal time consistent tax is always lower than the optimal tax in the case of pre-commitment so that, as a consequence, voluntary environmental innovation is always higher when there is no government pre-commitment (but welfare may be lower). This means that in the case of no-commitment, voluntary approaches (VA) would be more prevalent despite a reduction in social welfare. In both papers the VA is acting as a pre-commitment device which solves the dynamic inconsistency problem. In the present paper, we consider a similar setting allowing for oligopolistic interaction in a closed economy and concentrate on the case of a non-committal government to capture the VA element. The question we address relates to the organizational structure of environmental R&D, cooperative versus independent, and how this relates to the relative performance in terms of abatement (environmental innovation) and social welfare.

We examine two scenarios with respect to the organization of environmental R&D: (i) independent R&D and (ii) an industry-wide environmental R&D cartel (ERC). In the first scenario the structure of the multi-stage game is as follows: (1) firms choose their emission-reducing R&D non-cooperatively, (2) the regulator (or government) sets the emission tax and (3) firms compete in the market by choosing quantities. In the second scenario both the second and third stages remain the same, however, in the first stage firms form an industry-wide R&D Cartel that cooperatively undertakes environmental R&D.[1] Thus, in both R&D scenarios, the regulator follows a time-consistent policy.

We show that, contrary to the conventional presumption, an ERC can be detrimental to both emission reduction and social welfare. In particular, for relatively small damages, environmental innovation is higher in the case of an ERC compared to independent R&D, while for relatively large damages the opposite is true. The same ranking applies to the comparison of social welfare. However, firms always have an incentive to be part of an industry-wide ERC as this increases their profitability.

2 The Model

We consider a duopoly where firms produce a homogeneous good under a linear demand specification $p = a - Q$, $Q = q_i + q_j$, $i \neq j$, $i, j = 1, 2$, where a is a measure of market size. Production generates pollution which is taxed at the rate t on emissions while firm i can reduce its tax burden by undertaking environmental innovation (or abatement - we will use these terms interchangeably) z_i to reduce its emissions. The cost function for firm i is given by $c(q_i, z_i) = cq_i + \frac{\gamma z_i^2}{2}$ where c is the unit cost of production ($a > c$), i.e. there are constant returns to scale and γ captures the efficiency of the abatement technology. Notice that abatement is characterized by decreasing returns as we assume $\gamma > 0$. Firm i's emissions are given by $e_i(q_i, z_i) = q_i - z_i - \beta z_j$, $0 \leq \beta \leq 1$, i.e. there are knowledge spillovers in environmental R&D in that a firm benefits not only from its own R&D effort but also from its rival's effort by an amount β. Thus, by investing and amount $\frac{\gamma z_i^2}{2}$ in environmental R&D firm i can reduce its emissions by $z_i + \beta z_j$ - this latter term represents the effective R&D for firm i. Given pollution, the extent of damage is captured via a quadratic damage function, $D = \frac{1}{2} dE^2$, where $E = e_i + e_j$ is total emissions and d is proportional to marginal damage. To guarantee an interior solution for abatement we assume that $d > \frac{1}{2}$. In the sequel we compare the two alternative R&D scenarios: independent R&D and environmental R&D cartel (ERC).

[1] Scott (1996) reports that R&D cooperation takes place in response to both actual and anticipated regulation.

2.1 Non-cooperative R&D

2.1.1 Output Choice (Stage 3)

In the third stage, firm i chooses output to maximize profit

$$\max_{q_i} \left[(a - q_i - q_j)q_i - cq_i - \frac{\gamma z_i^2}{2} - t(q_i - z_i - \beta z_j)\right]$$

The relevant f.o.c. yields $q_i = (A - t - q_j)/2$, where $A \equiv a - c$. Imposing symmetry, $q_i = q_j = q^*$, we obtain equilibrium output per firm, $q^* = \frac{A-t}{3}$, and equilibrium profit $\pi_i^* = {q^*}^2 + t(z_i + \beta z_j) - \frac{1}{2}\gamma z_i^2$. Note that a firm's output decreases in the emission tax.

2.1.2 Regulator's choice of emission tax (Stage 2)

In the second stage, the regulator sets the emission tax, t, to maximize social welfare, expressed as the sum of producer and consumer surplus minus environmental damages,

$$\max_t \left[\int_0^{2q^*} (a - c - x)dx - \frac{1}{2}d[2q^* - (1+\beta)\sum_i z_i]^2 - \frac{1}{2}\gamma(\sum_i z_i^2)\right]$$

or equivalently

$$\max_t \left[2Aq^* - \frac{1}{2}(2{q^*}^2) - \frac{1}{2}d(2q^* - (1+\beta)\sum_i z_i)^2 - \frac{1}{2}\gamma(\sum_i z_i)^2\right]$$

The first-order condition is

$$2\left[A - 2q^* - d(2q^* - (1+\beta)\sum_i z_i)\right]\frac{dq^*}{dt} = 0$$

which, after some manipulation yields

$$t^* = \frac{(2d-1)A - 3d(1+\beta)\sum_i z_i}{2(1+d)} \tag{1}$$

From (1) notice that $\frac{dt^*}{dz_i} = -\frac{3d(1+\beta)}{2(1+d)} < 0$, so that a greater investment in R&D will lead to a lower emission tax; this captures the voluntary approach element in the model. Using (1) in the expression for output and profit we obtain

$$q^* = \frac{A + d(1+\beta)(z_i + z_j)}{2(1+d)} \tag{2}$$

and

$$\pi_i^* = \frac{[A + d(1+\beta)(z_i + z_j)]^2}{4(1+d)^2} + \frac{(2d-1)A - 3d(1+\beta)(z_i+z_j)}{2(1+d)}(z_i + \beta z_j) - \frac{1}{2}\gamma z_i^2 \tag{3}$$

2.1.3 Environmental R&D selection (Stage 1)

In the first stage of the game the two firms choose their environmental R&D anticipating the choice of tax by the regulator and the subsequent product market competition. Each firm maximizes second-stage profits as given by (3), so that the relevant first-order condition is

$$\frac{\partial \pi_i^*}{\partial z_i} = \frac{2d(1+\beta)[A + d(1+\beta)(z_i + z_j)]}{4(1+d)^2} + \frac{(2d-1)A - 3d(1+\beta)[2z_i + (1+\beta)z_j]}{2(1+d)} - \gamma z_i$$

In the symmetric equilibrium, $z_i = z_j = z_{nc}$, the solution of the f.o.c. yields the equilibrium level of abatement

$$z_{nc} = \frac{[(1+d)(2d-1) + d(1+\beta)]\,A}{2\gamma(1+d)^2 + d(1+\beta)[3(3+\beta) + d(7+\beta)]} \tag{4}$$

Using (4) into (1) and (2) we obtain the equilibrium emission tax and quantity per firm respectively

$$t_{nc} = \frac{d(2d-3)(1+\beta)^2 + 2\gamma(2d^2 + d - 1)}{2d(1+\beta)[3(3+\beta) + d(7+\beta)] + 4\gamma(1+d)^2}A \tag{5}$$

$$q_{nc} = \frac{2(1+d)\gamma + d(1+\beta)(7 + 4d + 3\beta)}{2d(1+\beta)[3(3+\beta) + d(7+\beta)] + 4\gamma(1+d)^2}A \tag{6}$$

Further,

$$\pi_{nc} = q_{nc}^2 + t_{nc}(1+\beta)z_{nc} - \frac{1}{2}\gamma z_{nc}^2 \tag{7}$$

and

$$TW_{nc} = 2Aq_{nc} - 2q_{nc}^2 - 2d(q_{nc} - (1+\beta)z_{nc})^2 - \gamma z_{nc}^2 \tag{8}$$

This concludes the analysis of the non-cooperative R&D scenario.

2.2 Cooperative R&D - Environmental R&D Cartel

Stages 2 and 3 remain the same. However, in the first stage the two firms choose their environmental R&D cooperatively, i.e. they choose $z_i, i = 1, 2$, to maximize joint profits. Notice that this is an environmental R&D cartel (ERC) as it operates with the same spillover as the independent firms, i.e. firms coordinate their R&D but do not share information fully - in the case where firms would share information completely we would have an environmental research joint venture (ERJV), i.e. $\beta = 1$ (see Kamien et al. (1992) for more details on the terminology used, adapted here for the environmental context).

Thus, in stage 1 firms maximize

$$\Pi_{erc} = \sum_i \pi_i - \frac{1}{2}\gamma \sum_i z_i^2$$

where π_i refers to the second-stage profit as given by (3). The first-order conditions require that $\frac{\partial \pi_{erc}}{\partial z_i} = 0 = \frac{\partial \pi_{erc}}{\partial z_j}$; deriving the f.o.c. and then setting $z_i = z_j = z_{erc}$, yields the symmetric equilibrium values [2] ,

$$z_{erc} = \frac{[(1+d)(2d-1)+2d](1+\beta)A}{2(1+d)^2\gamma + 4d(3+2d)(1+\beta)^2} \tag{9}$$

Using (9) into the relevant expressions for the emission tax and the quantity produced we obtain

$$t_{erc} = \frac{[d(2d-3)(1+\beta)^2 + \gamma(2d^2+d-1)]A}{2(1+d)^2\gamma + 4d(3+2d)(1+\beta)^2} \tag{10}$$

$$q_{erc} = \frac{[d(5+2d)(1+\beta)^2 + \gamma(1+d)]A}{2[\gamma + 2d(3+\gamma) + d^2(4+\gamma)]} \tag{11}$$

Furthermore, profits per firm and total welfare are expressed as

$$\pi_{erc} = q_{erc}^2 + t_{erc}(1+\beta)z_{erc} - \frac{1}{2}\gamma z_{erc}^2 \tag{12}$$

and

$$TW_{erc} = 2Aq_{erc} - 2q_{erc}^2 - 2d(q_{erc} - (1+\beta)z_{erc})^2 - \gamma z_{erc}^2 \tag{13}$$

Having described the cooperative R&D scenario we proceed to a comparison of the two different forms of R&D organization.

[2]The second-order conditions are satisfied.

2.3 A Comparison: Independent R&D versus ERC

First, we compare the R&D levels (abatement), z_{erc} and z_{nc}. From (9) and (4)

$$z_{erc} - z_{nc} = \frac{Ad(1+d)^2\varphi}{\Gamma\Delta} \tag{14}$$

where $\varphi \equiv d(3-2d)(1+\beta)^2(1-\beta)+2\gamma(2d^2\beta+2d\beta-\beta+d)$, $\Gamma \equiv 2\gamma(1+d)^2 + d(1+\beta)[3(3+\beta)+d(7+\beta)] > 0$ and $\Delta \equiv 2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2 > 0$. Further, from (10) and (5) we have

$$t_{erc} - t_{nc} = \frac{-3A(1+d)(1+\beta)\varphi}{2\Gamma\Delta} \tag{15}$$

We then state and prove the following:

Proposition 1 *For $\beta \in [0,1], \gamma > 0$ and $d > \frac{1}{2}$*
(i) for $\frac{1}{2} < d < \frac{3}{2}$ the equilibrium abatement in the ERC is always greater than the non-cooperative equilibrium abatement, $z_{erc} > z_{nc}$, while the optimal emission tax in the case of an ERC is lower than the optimal emission tax in the non-cooperative equilibrium, $t_{erc} < t_{nc}$;
(ii) for a given d, $d > \frac{3}{2}$, there exists a critical value for the R&D efficiency parameter, $\overline{\gamma}$, such that $z_{erc} > z_{nc}$ if and only if $\gamma > \overline{\gamma}$ and $z_{erc} < z_{nc}$ if and only if $\gamma < \overline{\gamma}$. Further, for $\gamma > \overline{\gamma}$, $t_{erc} < t_{nc}$ and for $\gamma < \overline{\gamma}$, $t_{erc} > t_{nc}$. The critical value $\overline{\gamma}$ is decreasing in the spillover, β, and increasing in the damage parameter, d.
(iii) for $d > \frac{3}{2}$ and for a given γ, there is a critical value[3] $\overline{d}$ such that for $d > \overline{d}$, the equilibrium abatement in the ERC is lower than the non-cooperative equilibrium abatement, $z_{erc} < z_{nc}$ and for $d < \overline{d}$, $z_{erc} > z_{nc}$. Further, for $d > \overline{d}$, $t_{erc} > t_{nc}$ while for $d < \overline{d}$, $t_{erc} < t_{nc}$.

Proof From (14) and (15), $z_{erc} \gtrless z_{nc}$ and $t_{erc} \lessgtr t_{nc}$ respectively, if and only if $\varphi \gtrless 0$, $\varphi \equiv d(3-2d)(1+\beta)^2(1-\beta) + 2\gamma(2d^2\beta + 2d\beta - \beta + d)$.
(i) The second term in the above expression for φ is positive for all admissible values of d and β. The first term is positive if and only if $d < \frac{3}{2}$ (recall that $d > \frac{1}{2}$ by assumption) and thus, $\varphi > 0$.
(ii) Let $d > \frac{3}{2}$. Next define $\overline{\gamma} \equiv \{\gamma \mid \varphi = 0\} = \frac{1}{2}\frac{d(2d-3)(1+\beta)^2(1-\beta)}{2d^2\beta+2d\beta-\beta+d} > 0$, as the critical R&D efficiency parameter. Note that $\partial\varphi/\partial\gamma = 2(2d^2\beta + 2d\beta - \beta + d) > 0$ so that $\varphi \geq 0$ if and only if $\gamma \geq \overline{\gamma}$ and $\varphi < 0$ if and only if $\gamma < \overline{\gamma}$. Moreover, $\partial\overline{\gamma}/\partial\beta \propto -[(d-1) + \beta(1+d) + 2d^2(1-\beta) + \beta^2(4d^2 + 4d - 2)] < 0$ and $\partial\overline{\gamma}/\partial d \propto 2d^2 + \beta(10d^2 - 4d + 3) > 0$.

[3] The exact solution for the critical value $\overline{d}$ is available upon request.

(iii) Let $d > \frac{3}{2}$. Next, define $\overline{d} \equiv \{d \mid \varphi = 0\}$ as the critical environmental parameter. For $\beta = 0$, $\varphi = d(3 - 2d + 2\gamma) \gtrless 0$ and given γ there exists $\overline{d}$, $\overline{d} = \gamma + \frac{3}{2} > 0$, such that if $d > \overline{d}$, then $z_{erc} < z_{nc}$ and if $d < \overline{d}$ then $z_{erc} > z_{nc}$. For $\beta = 1$, $\varphi = 2\gamma[d(3 + 2d) - 1] > 0$ so that $z_{erc} > z_{nc}$. Then, by continuity, for $\beta \in (0, 1)$ there exists a critical value $\overline{d}$ such that for $d > \overline{d}$, $z_{erc} < z_{nc}$ while for $d < \overline{d}$, $z_{erc} > z_{nc}$. The argument for the emission tax is identical except for a reversal in the inequalities, see (15).■

Corollary 1 *When $\beta = 1$, i.e. there is an environmental research joint venture (ERJV) with full information-sharing, it will spend more in environmental R&D (and hence will face a lower emission tax) for any value of d.*

Proof From (14), $z_{erc} > z_{nc}$ if and only if $\varphi > 0$. For $\beta = 1$, $\varphi = 2\gamma[d(3 + 2d) - 1] > 0$. The argument for the emission tax is analogous and hence omitted. ■

Figure 1 illustrates the above proposition and the corollary.

[Figure 1]

Thus, according to Proposition 1, for relatively small environmental damages ($\frac{1}{2} < d < \frac{3}{2}$) abatement is higher with the environmental R&D cartel irrespective of the extent of R&D efficiency (part i). However, when environmental damages are larger, $d > \frac{3}{2}$, the comparison between the two different forms of R&D organization is less clear-cut. For a given d it hinges on the efficiency of R&D: for relatively efficient R&D ($\gamma < \overline{\gamma}$) abatement is lower with the environmental R&D cartel while the opposite is true for inefficient R&D ($\gamma > \overline{\gamma}$), as expected intuitively. Further, as the spillover increases the critical value for the R&D efficiency parameter decreases so that the ERC outperforms the independent R&D set-up in a wider class of cases (part ii). More interestingly, for a given γ, for relative large damages ($d > \overline{d} > \frac{3}{2}$) abatement is lower with the environmental R&D cartel while the opposite is true for small damages ($\frac{3}{2} < d < \overline{d}$) (part iii). The opposite results hold for the optimal emission tax - this is a direct implication of the voluntary approach element, $\frac{\partial z}{\partial t} < 0$.

Our intuition for proposition 1 proceeds as follows: Consider the case of no spillovers for given R&D efficiency (fixed γ). In order to reduce its tax bill, a firm will increase its environmental R&D so as to induce a lower emission tax from the regulator; however, each firm will reason this way and will expect its rival firm to do the job, given the public good nature of emission reduction, resulting in underinvestment in R&D. When firms coordinate their R&D within an ERC, this free-riding aspect becomes internalized and firms will spend more relative to the case of independent R&D and will generate more abatement. However, as damage increases, independent firms stand to loose relatively more from a higher emission tax and thus for high values of d we observe that they will do more R&D than firms in the ERC. Taking account of the spillover, in the case of independent R&D there is further underinvestment due to the appropriability problem - this explains why as the spillover increases the firms in an ERC will undertake more R&D than the independent firms (in figure 1 the dark area decreases as the spillover increases). It is clear though that an ERC promotes environmental innovation only when damage is relatively small (and for a given value of the spillover).

Next, we compare equilibrium profits per firm. Using (7) and (12) after some manipulation we obtain

$$\pi_{erc} - \pi_{nc} = \frac{A^2(1+d)^2\kappa^2}{4\Delta\Gamma^2} > 0 \tag{16}$$

where $\kappa \equiv d(3-2d)(1-\beta)(1+\beta)^2 + 2\gamma[d+\beta(2d^2+2d-1)]$. We then state

Proposition 2 *Firm profitability is higher in an environmental R&D cartel (ERC) than in R&D competition,* $\pi_{erc} > \pi_{nc}$.

It is obvious that it is privately profitable for a firm to participate in an environmental R&D cartel whatever the environmental damage (and emission tax); i.e. a firm has a clear incentive to participate in an ERC.[4] This is expected given that within an ERC each firm is maximizing joint profits by choice of its environmental R&D.

Finally, we compare total welfare under the two forms of R&D organization. The following proposition summarizes the results.

Proposition 3 *For given* γ , $\beta \in [0,1]$ *and* $d > \frac{1}{2}$
(i) when $\frac{1}{2} < d < \frac{3}{2}$ *total welfare in the ERC is always greater than in the non-cooperative equilibrium,* $TW_{erc} > TW_{nc}$;
(ii) when $d > \frac{3}{2}$, *there is a* $\overline{d}$ *such that for all* $d > \overline{d}$, *total welfare is lower in an environmental R&D cartel relative to environmental R&D competition* $TW_{erc} < TW_{nc}$ *and for all* $\frac{3}{2} < d < \overline{d}$, *the opposite is true,* $TW_{erc} > TW_{nc}$.

[4] In the case of a n firm oligopoly this incentive would be present in a situation of an industry-wide ERC. However, allowing k firms in an ERC ($k < n$) - or generally in various types of R&D cooperation, would necessitate a careful examination of the profitability/incentives to join of the outside firms. These issues lie outside the scope of the present paper.

Proof From (8) with (13) we obtain after some manipulations

$$TW_{erc} - TW_{nc} = \frac{A^2(1+d)^2\Omega\varphi}{4K^2\Lambda^2} \tag{17}$$

where $\Omega > 0$, $\Omega \equiv 2d^2(1+\beta)^4\omega_1 + d(1+\beta)^2\omega_2 + 2(1+d)^2\omega_3 > 0$, and $\omega_1 \equiv [3(7+\beta) + d(51+13\beta + d(26+6\beta))]$,
$\omega_2 \equiv [29 + 7\beta + d\,(36 + 28\beta + d\,(29 + 55\beta + 2d\,(7 + 13\beta)))]\,\gamma$,
and $\omega_3 \equiv [2 + \beta + d(2d\beta - 1)]\,\gamma^2$. Further, $K \equiv 6d + 4d^2 + 12d\beta + 8d^2\beta + 6d\beta^2 + 4d^2\beta^2 + \gamma + 2d\gamma + d^2\gamma$, $\Lambda \equiv 9d + 7d^2 + 12d\beta + 8d^2\beta + 3d\beta^2 + d^2\beta^2 + 2\gamma + 4d\gamma + 2d^2\gamma$ and φ has been defined previously. It is then obvious that $sign[TW_{erc} - TW_{nc}] = sign(\varphi)$. We can then use the formal similarity with the proof of Proposition 1 (parts (i) and (iii)) to obtain the result. ■

According to Proposition 3, an environmental R&D cartel can be detrimental to social welfare despite being desirable from the firms' point of view; this is so for relative large environmental damages and efficient R&D. The intuition for this result is a direct implication of the result on the relative ranking of environmental R&D, contained in proposition 1. Note also, when $\beta = 1$, the ERC (which in this case coincides with an ERJV) outperforms the independent R&D case for any degree of environmental damage - this is because it internalizes totally both the free-rider and the appropriability problems.

3 Concluding Remarks

In this paper we have addressed the question of whether the organization of environmental R&D is important in relation to emission reduction and the associated total welfare. This has been examined in the context of a voluntary approach formulation captured by the inability of the regulator/government to commit to the environmental policy instrument (emission tax) credibly. It has been shown that, for relatively small damages, environmental innovation is higher in the case of an environmental R&D cartel (ERC) compared to independent R&D, while for relatively large damages the opposite is true. The same ranking applies to the comparison of social welfare. In addition, the time-consistent tax is lower for an ERC compared to independent R&D in the case of small damages and the reverse holds for large damages. It would seem then, in summary, that ERCs perform better than a non-cooperative R&D organization only when environmental damage is low. We should note though that these results have been obtained in the context of a duopolisitic market. Extending the analysis to an n-firm oligopoly would exacerbate the free-rider problem so that cooperation in the form of an environmental R&D cartel would most probably result in higher abatement and welfare in a wider class of cases; however, with more than two firms we would have to consider cooperation encompassing less than the total number of firms in the market and examine the effects on insiders (cooperating firms) and outsiders (non-cooperating firms) and how the interplay of these sets of firms affects total welfare and so on. Moreover, issues of multiple, competing ERCs would need to be addressed. We leave these interesting topics for future research.

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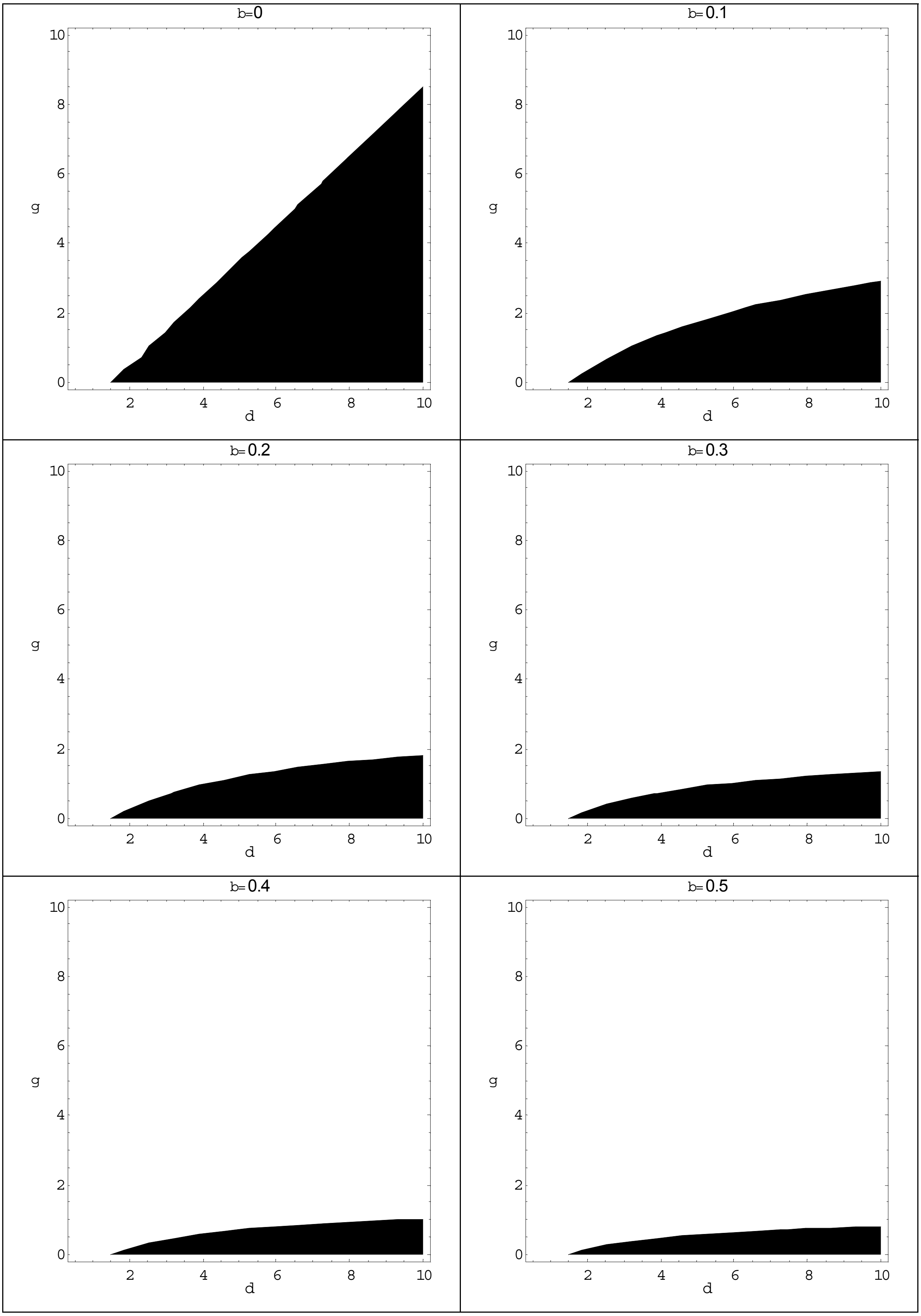
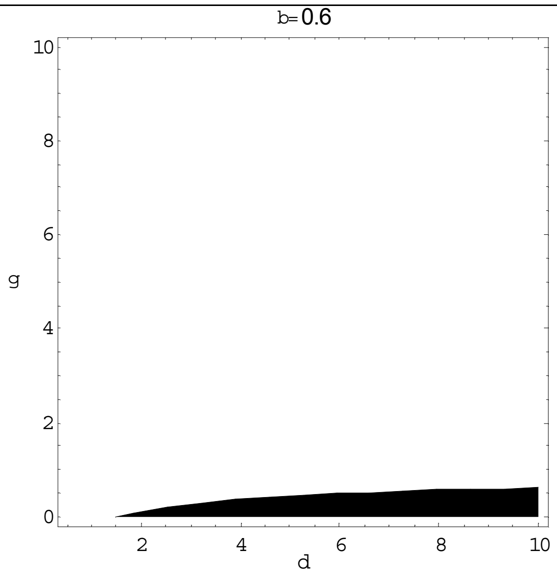
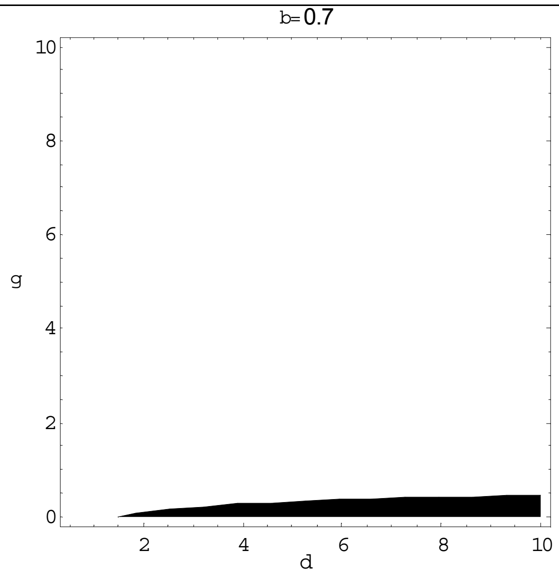
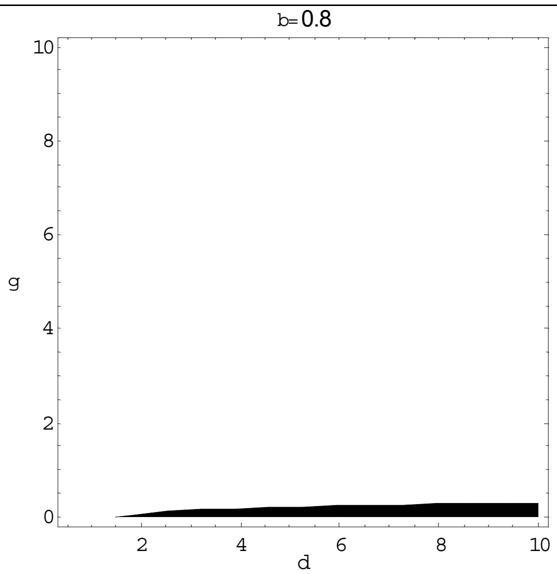
Figure 1

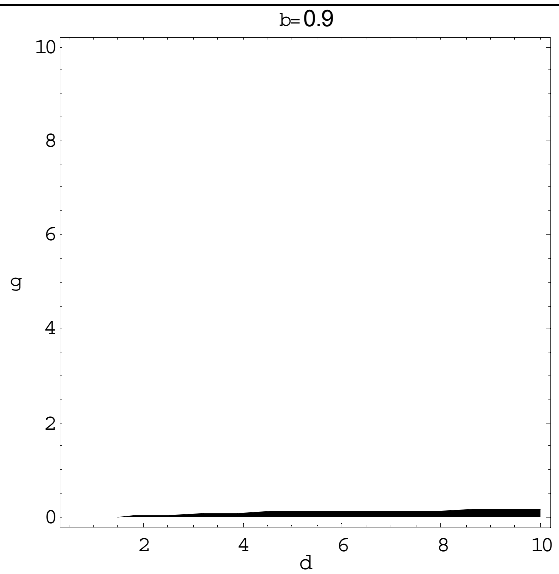
Environmental R&D (emission reduction)

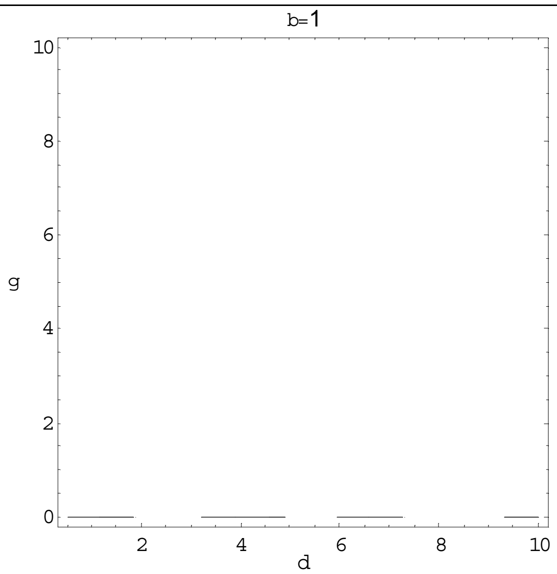












Note: The white area in each cell corresponds to $z_{erc} > z_{nc}$ and the black area represents $z_{erc} < z_{nc}$.

z_{erc}: environmental R&D per firm in the ERC

z_{nc}: environmental R&D per firm under independent R&D