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Voluntary approaches, emission taxation and the organization of environmental R&D

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Abstract

In this paper we consider a setting where firms commit to environmental R&D expenditure that reduces their emission levels before the regulator sets the emission tax. 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 (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 is unable to commit credibly to the emission tax.

We show 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

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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 (1999) 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 (e.g.Conrad (1998) and Petrakis and Xepapadeas (1999)). 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 unilateral voluntary approach). Petrakis and Xepapadeas (1999) 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 possible 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 government or regulator who possess very limited commitment power 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 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). [1] Environmental R&D affects the emissions of a firm in

[1] This terminology is adapted for the case of polluting emissions following Kamien et al. (1992) who have provided a classification of different R&D organizational forms in the

the sense that by undertaking it a firm can reduce its polluting emissions; further, we posit that there are knowledge spillovers in the R&D process so that a firm can benefit from the R&D expenditure of its rival at no cost to itself. 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. In both scenarios, emissions are reduced by a firm's own R&D effort, in addition to some spillover from other firms' R&D. In the ERC the spillover is not increased because of the cartelization. Note that in both R&D scenarios, the regulator follows a time-consistent policy. [2]

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.[3]

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 z_i (or environmental R&D - we will use these terms interchangeably) 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

absence of pollution effects for the case of cost-reducing R&D.

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

[3] Using numerical simulations, Katsoulacos et al. (1999) in a complementary analysis obtain a similar result for the case of a research joint venture. However, their model focuses on the issue of information-sharing and the optimal number of research laboratories within environmental research joint ventures when the outcome of R&D is subect to R&D output spillovers and uncertainty whereas (as will become clear in the following sections) our model concentrates on the case of R&D characterised by R&D input spillovers while keeping clear from the issue of information-sharing.

of the R&D technology. Notice that environmental R&D 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.[4] 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 environmental R&D 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).

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

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

[4] This type of spillover is an R&D input spillover.

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 effect 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

$$\begin{aligned}\pi_{i}^{*} &= \frac{[A+d(1+\beta)(z_{i}+z_{j})]^{2}}{4(1+d)^{2}}+ \\ &\quad \frac{(2d-1)A-3d(1+\beta)(z_{i}+z_{j})}{2(1+d)}(z_{i}+\beta z_{j})-\frac{1}{2}\gamma z_{i}^{2}\end{aligned} \tag{3}$$

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

$$\begin{aligned}\frac{\partial \pi_{i}^{*}}{\partial z_{i}} &= \frac{2d(1+\beta)[A+d(1+\beta)(z_{i}+z_{j})]}{4(1+d)^{2}} \\ &\quad +\frac{(2d-1)A-3d(1+\beta)[2z_{i}+(1+\beta)z_{j}]}{2(1+d)}-\gamma z_{i}\end{aligned}$$

In the symmetric equilibrium, $z_{i}=z_{j}=z_{nc}$, the solution of the f.o.c. yields the equilibrium level of environmental R&D

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

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

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

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

Further,

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

and

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

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

2.2 Cooperative R&D - Environmental R&D Cartel

As mentioned in the introduction, stages 2 and 3 remain the same. However, in the first stage the two firms choose their environmental R&D cooperatively, i.e. they coordinate their R&D activities, i.e. choose $z_i, i = 1, 2$, to maximize the sum of their overall profit. 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. $\beta = 1$.[5]

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 [6] ,

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

[5] Kamien et al. (1992) refer to an RJV scenario (research joint venture cartel in their terminology) as a situation where firms coordinate their R&D activities so as to maximize the sum of their overall profit while at the same time they share R&D efforts and avoid duplication of R&D activities. Further, the spillover is increased to its maximal level.

[6] The second-order conditions are satisfied.

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.

2.3 A Comparison: Independent R&D versus ERC

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

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

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) when $\frac{1}{2} < d < \frac{3}{2}$ the equilibrium R&D in the ERC is always greater than the non-cooperative equilibrium R&D, $z_{erc} > z_{nc}$, 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*[7] $\overline{d}$ *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 $t_{erc} \lesseqgtr t_{nc}$ 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 $\partial\overline{\gamma}/\partial d \propto 2d^2 + \beta(10d^2 - 4d + 3) > 0$.
(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 $d < \overline{d}$, $z_{erc} > z_{nc}$. It can be shown that $\overline{d}$ is increasing in β. 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. ■

Thus, according to Proposition 1, for relatively small environmental damages ($\frac{1}{2} < d < \frac{3}{2}$) environmental R&D is higher with the ERC 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

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

R&D: for relatively efficient R&D ($\gamma < \overline{\gamma}$), environmental innovation 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 ($d > \overline{d} > \frac{3}{2}$) environmental innovation 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 part (iii) of 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, given the public good nature of emission reduction, each firm will reason this way and will expect its rival firm to do the job 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 emission reduction. 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.

Figure 1 illustrates the above proposition and the corollary.

[Figure 1]

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

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

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.[8] 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,* $TW_{erc} > TW_{nc}$*.*

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. However, for relatively small damages, the ERC results in higher welfare than independent R&D. This latter result is in contrast with the general result obtained in the cost-reducing R&D literature, where an R&D cartel is the worst form or R&D organization in terms of social welfare relative to independent R&D and a research joint venture (which is the most closer to the

[8] 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 for the outside firms. These issues lie outside the scope of the present paper.

social optimum), see e.g. Kamien et al. (1992). Introducing pollution effects results in a change in the welfare ranking of R&D organizational forms. The intuition for these results is a direct implication of the results 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.[9]

3 Concluding Remarks

In this paper we have addressed the question of the importance of the organization of environmental R&D in relation to emission reduction and the associated social welfare. We have examined this in the context of a unilateral voluntary approach formulation captured by the inability of the regulator/government to commit to the environmental policy instrument (in this case an emission tax) credibly. We have 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. However, we should be aware that this tentative conclusion has been reached for the case where the environmental policy tool is a tax on a firm's emissions. By using a different policy instrument, for example an ambient tax (imposed on total emissions), the regulator might be able to induce firms to internalize their actions on other firms. This observation leads us to suggest studying the impact of a change in the tax design to examine how the possible welfare differences between independent R&D and an ERC depend on the instrument used by the regulator. Further, and in relation to the result about the superiority of an ERJV (under which firms share information fully) for any degree of damage, the role of policy might be

[9] This is in contrast with the result obtained by Katsoulacos et al. (1999), where an ERJV was shown to outperform independent R&D for the case of small damages only in the context of R&D output spillovers though. Note that in our model, it is assumed that within an ERJV full information-sharing takes place; in a context of cost-reducing R&D, Poyago-Theotoky (1999) has shown that the choice of $\beta = 1$ is the unique equilibrium outcome of a game where (input) spillovers are endogenous under the influence of firms.

to facilitate information exchange between firms in order to transform any voluntary ERC into a welfare-improving ERJV.

In addition, we should note 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 probably result in higher environmental innovation 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.[10] We leave these interesting topics for future research.

[10] On this see Kamien and Zang (1993) for the case of cost-reducing R&D in the absence of pollution effects.

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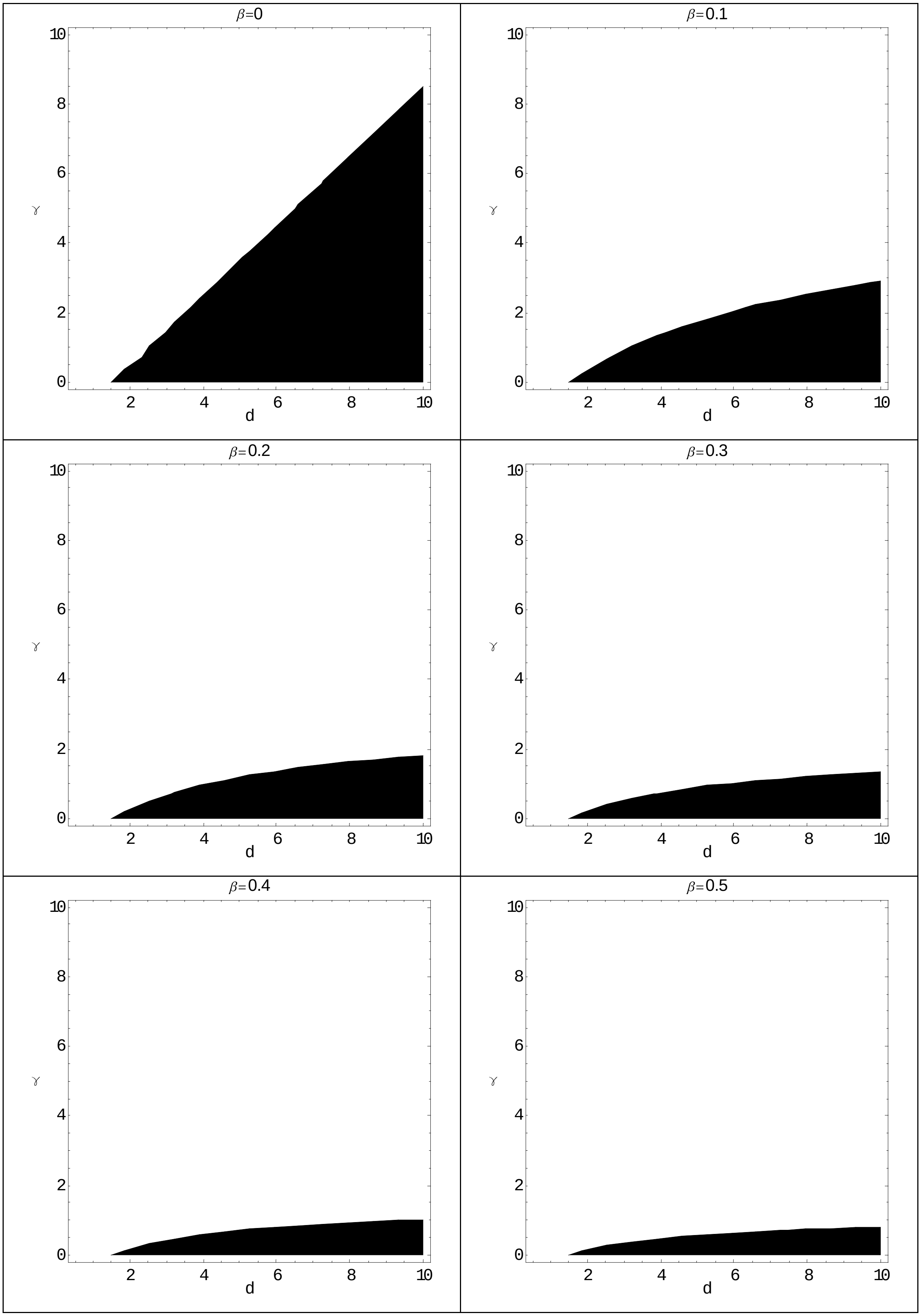
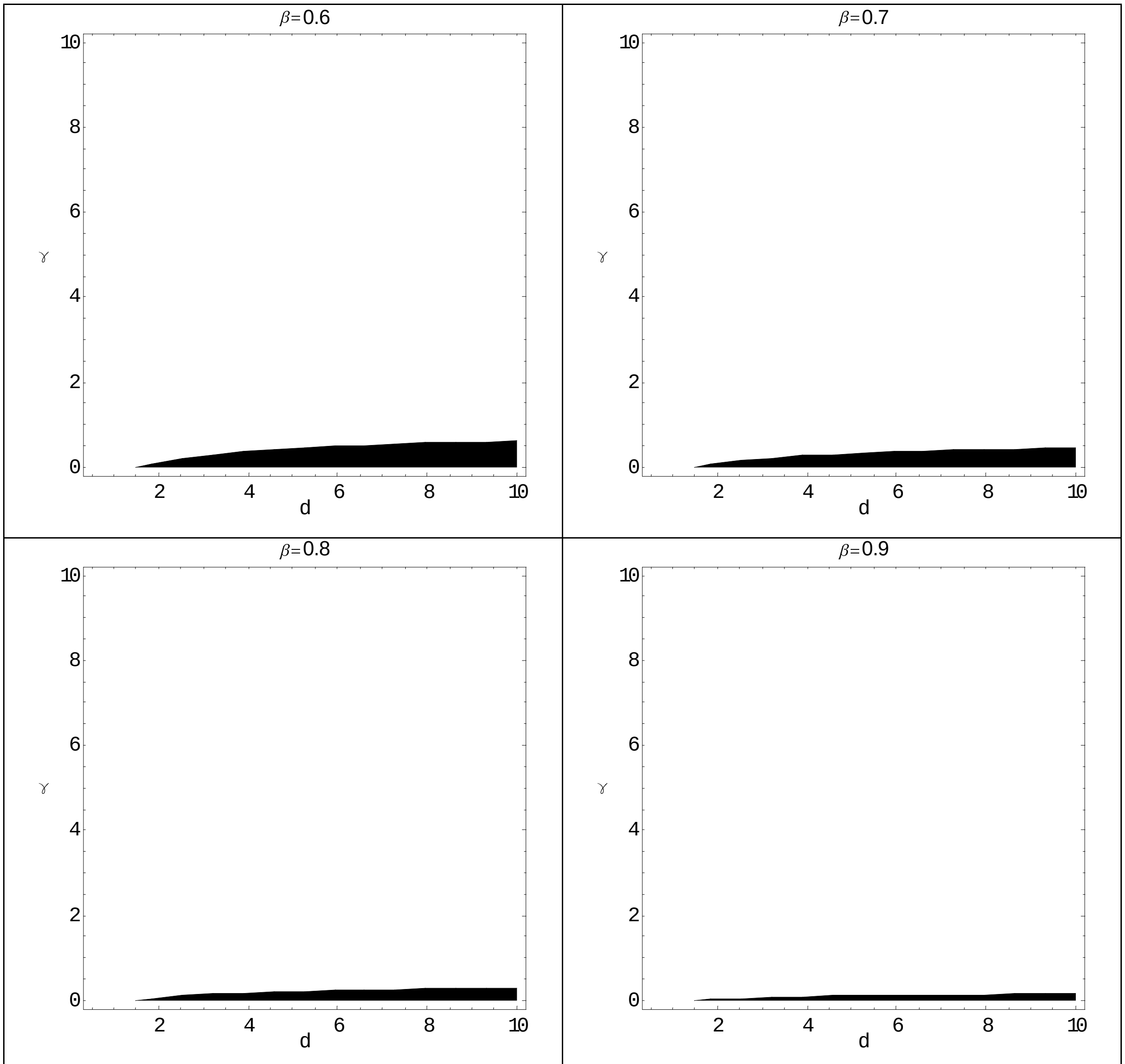
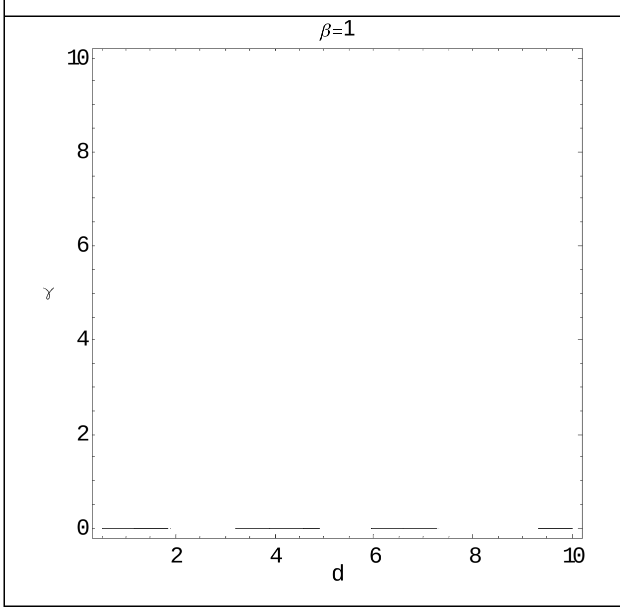
Figure 1

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