TECHNOLOGY POLICY IN AN OLIGOPOLY WITH SPILLOVERS AND POLLUTION[‡]

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ABSTRACT

We introduce pollution, as a by-product of production, into a non-tournament model of R&D with spillovers. Technology policy takes the form of either R&D subsidisation or pre-competitive R&D cooperation. We show that, when the emissions tax is exogenous, the optimal R&D subsidy can be negative, i.e. there should be a tax on R&D, depending on the extent of the appropriability problem and the degree of environmental damage. In a wide class of cases, depending on the parameter values, welfare in the case of R&D cooperation, is lower than welfare in the case of R&D subsidisation. In addition, a policy of tying-in the R&D subsidy to abatement results in an allocation where firms undertake the optimal (in a second-best sense) abatement level and social welfare improves.

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1. Introduction

The issue of technology policy in imperfectly competitive markets has received considerable attention both in the theoretical and applied literature. Several papers in the industrial organisation literature discuss the relative merits of different policy instruments, such as R&D subsidies and the encouragement of cooperative R&D, in addressing the appropriability problem in order to raise R&D output, firm profitability and social welfare [e.g. Kamien *et al.* (1992), Vonortas (1994), Poyago-Theotoky (1995) and Leahy and Neary (1997)]. However, an aspect which has been largely ignored by this strand of literature consists in the potentially adverse impact that technology policy might have on the environment through increased production when R&D results in cost reduction. Technology policy measures, such as e.g. R&D subsidies or the formation of Research Joint Ventures (RJVs), that encourage firms to reduce their production costs, would usually reduce energy inputs and therefore generate less pollution per unit of output produced. Here we explore the situation where with a reorganisation of production total output increases. Thus even if per unit of production pollution is less, total pollution generated by the increased production, which is induced by the innovative efforts of firms, increases.

Contributions from the environmental economics literature have examined issues related to environmental policy within imperfectly competitive markets concentrating on the externality problem resulting from firms' pollution generating activities. D. Ulph (1994) and A. Ulph (1996) examine the effect that environmental policy has on R&D incentives and consider the relative performance of emissions taxes versus standards on abatement related R&D expenditure. Katsoulacos and Xepapadeas (1996a,b) provide an analysis of the optimal policy rules in a Cournot oligopoly with spillovers and environmental innovation and characterise the optimal emissions tax and the optimal subsidy to abatement R&D.

To the best of our knowledge, the impact of technology policy on the environment in an oligopoly has not been considered so far. Yet, this is an important issue with practical consequences. This paper is an attempt to partially fill this gap. More precisely, we study the impact of two different policies, R&D subsidies and R&D cooperation, in a duopoly model with cost-reducing R&D, spillovers and abatement. Our setting departs in two respects from the existing studies. First, we assume that firms' production activities generate pollution as a by-product. Second, we postulate that the emissions tax is exogenous, i.e. beyond the control of the regulator/government who sets the technology policy.[1] We believe that there are a certain number of cases where the emissions tax can be seen as fixed. For instance, the tax may be set at a supra-national level (such as the European Union) affecting a number of industries whereas technology policy is aimed at a particular industry in a given economy. Alternatively, it might be easier to legislate and implement local technology policy measures whereas it might be very difficult to change an emissions tax affecting a number of economies. As an additional justification for the exogenous emissions tax we mention the case where environmental policy is set at a national level by, say, the ministry of the environment, while technology policy is sector/industry specific and is set by, say, the ministry of technology. Within the context of a partial equilibrium analysis this sector/industry is small in comparison to the whole economy. As the design of the environmental policy is based on aggregate emissions and given that the industry under consideration is small its emissions are not important in the determination of the emissions tax for the whole economy.

Firms choose their cost-reducing R&D but they also undertake abatement to reduce their tax bill before choosing their production plans. In this setting we can deal with a number of important issues. First, in the case of a policy of R&D subsidisation, the question arises as to whether the optimal R&D subsidy could be negative. Second, it is interesting to investigate under what conditions (if any) cooperative R&D results in lower welfare relative to R&D subsidisation; this would run contrary to the conventional wisdom pertaining to the desirability of R&D

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[1] Katsoulacos and Xepapadeas (1996 a,b) allow for an endogenous emissions tax but do not consider cost-reducing R&D.

cooperation. Third, given the fixed emissions tax, it is worth examining whether the policy of tying-in the R&D subsidy to abatement can lead to a better allocation.

Our model is based on a specification introduced by D'Aspremont and Jacquemin (1988) suitably extended to accommodate the environmental dimension of production. We concentrate on an industry in which each of two firms offers a homogeneous product. Firms choose abatement and cost-reducing R&D and then output. Unit production costs are constant but can be reduced by firms' R&D through spillovers; R&D and abatement costs are increasing at an increasing rate. Thus, our analysis is cast within a partial-equilibrium framework.

Our results are as follows. We first show that in the case of R&D subsidisation the optimal R&D subsidy can be negative, i.e. there should be a tax on R&D, depending on the extent of the appropriability problem (as expressed in the spillover value) and the degree of environmental damage. Hence, the familiar result that the optimal R&D subsidy is positive is (partially) reversed in our setting. Then we establish the circumstances under which welfare in the case of R&D cooperation is lower than welfare in the case of R&D subsidisation. Finally, in the light of this latter result, we show that a policy of tying-in the R&D subsidy to abatement effort results in an allocation where firms undertake the optimal (in a second-best sense) abatement level and social welfare improves. Hence, the tied-in R&D subsidy has a dual effect: on the one hand it addresses the appropriability problem and on the other hand it also deals with the pollution problem.[2]

The remainder of the paper is organised as follows. In section 2 the model is introduced and the cases where technology policy takes the form of R&D subsidisation and R&D cooperation are analysed and compared in terms of welfare. Section 3 proposes a novel scheme of conditional on abatement effort R&D subsidisation that improves welfare. Finally, section 4 concludes. All proofs are relegated to the Appendix.

2. The model

Consider a duopoly with firms producing a homogeneous good under constant returns to scale. Unit costs can be reduced by R&D spending while one firm can benefit from the other firm's R&D, i.e. there are spillovers. Technology policy takes the form of a subsidy towards the costs of R&D; we also consider the case where firms form a research joint venture (RJV). Pollution is a by-product of the production process. Firms are faced with an exogenously set emissions tax but can undertake abatement efforts in order to reduce their emissions and hence their tax burden.

Let demand for the product be linear, $P = a - Q$, where $Q = q_1 + q_2$. The cost function for firm i, $i = 1,2$, is additively separable in production costs, R&D costs and abatement expenditure, i.e. $c(q_i, z_i, w_i) = c_i q_i + (\gamma / 2) z_i^2 + w_i^2 / 2$, where z_i is cost-reduction and w_i is the abatement effort for firm i. That is, there are constant returns to scale in production, with unit costs of production constant at c_i; however, a firm can lower its unit cost by engaging in cost-reducing R&D and it can also benefit from its rival through spillovers. Unit costs are given by $c_i = c - z_i - \beta z_j$, $i \neq j, i, j = 1,2$, $\beta \in [0,1]$ is the spillover parameter, $c < a$ and $c > z_i + \beta z_j$. R&D costs are convex, indicating decreasing returns to scale: (i) by investing $\varphi(z_i) = (\gamma / 2) z_i^2$ in cost-reducing R&D, firm i can lower its unit cost by z_i, where γ represents the relative effectiveness of this type of R&D, and (ii) by investing $\psi(w_i) = w_i^2 / 2$ in environmental R&D (abatement) firm i can reduce its emissions by w_i. Emissions of the pollutant associated with the production of the good by firm i are $e_i(q_i, w_i) = q_i - w_i$; firm i incurs an (exogenous) tax on its emissions, t, so that by undertaking abatement it can reduce its tax burden.

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[2] In the case of an exogenous emissions tax set at the national level, industries are differentiated with respect to their environmental consequences so that additional measures may be needed to improve welfare. What we propose is exactly that: tied-in R&D subsidies play this role, i.e. they correct for industry-specific environmental damages.

Finally, the damage function is assumed to be quadratic in aggregate emissions, i.e. $D(q_1, q_2, w_1, w_2) = (d/2)[\sum_{i=1}^{2}(q_i - w_i)]^2$, where d is the steepness of the damage function. We assume that $0 \leq d \leq 2$ and $\gamma > (16/9)$ to guarantee interior and positive solutions for the abatement level, cost-reduction and output per firm.[3]

We examine two different set-ups concerning technology policy with respect to R&D: subsidised R&D and cooperative R&D. We thus consider two different games. In the first game, R&D costs are subsidised by the regulator/government who moves first by setting the subsidy rate. Next, firms choose how much abatement to do and how much to spend in cost-reducing R&D. Finally, they compete in the product market by choosing quantities. In the second policy set-up, there are no R&D subsidies but firms cooperate in setting their cost-reducing R&D so as to maximise joint profits. However, they compete in the product market. In what follows, we characterise the (subgame-perfect) equilibrium for both games and then provide a comparison of the two set-ups in terms of social welfare.

2.1 R&D Subsidies

Here technology policy takes the form of subsidising cost-reducing R&D expenditure but without allowing R&D cooperation.[4] In the first stage the government (or regulator) sets the subsidy, then firms choose their abatement level and the cost-reducing R&D simultaneously while at the same time receiving a subsidy, s, on their R&D costs. Thus, the R&D cost function becomes $c(z_i) = (1-s)(\gamma/2)z_i^2$, $-\infty \leq s < 1$.[5] Finally, firms compete in the product market by choosing output.

In the last stage, firm i chooses its output to maximise profits:

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[3] As will become evident later the upper value on d is necessary since if d is big enough and $t = 0$, a firm faces a high R&D tax on its R&D expenditure and thus has no incentive to carry out any cost-reducing R&D.

[4] See Hinloopen (1995) and Stenbacka and Tombak (1996) for a related analysis.

[5] Notice that we allow for a negative subsidy, i.e. a tax on R&D.

$$\max_{q_i}[(a-q_i-q_j)q_i-c_iq_i-\frac{1-s}{2}\gamma z_i^2-\frac{1}{2}w_i^2-t(q_i-w_i)] \tag{1}$$

with associated first-order condition,

$$a-q_i-q_j-c_i-t=q_i \tag{2}$$

from which we can obtain firm *i*'s optimal output and profit:

$$\hat{q}_i=\frac{(a-2c_i+c_j-t)}{3}=\frac{[a-c+(2-\beta)z_i+(2\beta-1)z_j-t]}{3} \tag{3}$$

$$\hat{\pi}_i=\hat{q}_i^2-\frac{(1-s)}{2}\gamma z_i^2-\frac{1}{2}w_i^2+tw_i \tag{4}$$

Note that output is decreasing in the emissions tax and (gross) profit is increasing in abatement. Recall that firms are engaged in both process innovation and abatement.

Process Innovation Selection[6]

Given the subsidy *s* on R&D costs, firm *i* will maximise its second stage profit as given by (4) by choice of z_i. The first-order condition is

$$2\hat{q}_i\frac{\partial\hat{q}_i}{\partial z_i}=(1-s)\gamma z_i$$

which, from (3)[7]

$$(2/9)(2-\beta)[A-t+(2-\beta)z_i+(2\beta-1)z_j]=(1-s)\gamma z_i \tag{5}$$

where $A = a - c$ is a measure of market size. In the symmetric equilibrium, $z_i^* = z_j^* \equiv z_s^*$:

$$z_s^*=\frac{2(2-\beta)(A-t)}{9\gamma(1-s)-2(2-\beta)(1+\beta)} \tag{6}$$

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[6] In solving the game we make use of the observation that the cost-reduction choice is unrelated to the abatement choice. Technically this means that we can proceed by solving the game sequentially.

[7] The second-order condition is $9\gamma(1-s)-2(2-\beta)^2>0$ and the stability condition requires $\left|2(2-\beta)(2\beta-1)/[9\gamma(1-s)-2(2-\beta)^2]\right|<1$. In what follows we make sure that both conditions are satisfied.

where $9\gamma(1-s)-2(2-\beta)(1+\beta)>0$ and we assume $A > t$. Using (6) we obtain output per firm

$$q_s^* = \frac{3\gamma(1-s)(A-t)}{9\gamma(1-s)-2(2-\beta)(1+\beta)} \tag{7}$$

and profit per firm is $\pi_s^* - (1\ \ 2)w_i^2 + tw_i$

$$\pi^* = \frac{\gamma(1-s)(A-\ \ )^2[(9\gamma(1-s)-2(2-\beta)^2]}{[9\gamma(1-s)-2(2-\beta)(1+\beta)]^2} \tag{8}$$

$9\gamma(1-s)-2(2-\beta)^2>0$ from the second-order condition. Note that setting $s = 0$, we obtain the equilibrium values for the case where there is no technology policy.

Environmental Innovation Selection

Firm i chooses its abatement effort, w_i, to maximise profits as given by $\pi_s^* - \frac{1}{2}w_i^2 + tw_i$. Since $\frac{\partial \pi_s^*}{\partial w_i} = 0$, from the first-order condition we obtain, in the symmetric equilibrium,

$$w_i^* = t \tag{9}$$

and profits become

$$\hat{\pi}_i = \pi_s^* + \frac{t^2}{2} \tag{10}$$

Note that if $t = 0$, then $w_i = 0$, i.e. in the absence of an emissions tax firms have no incentive to undertake abatement activities (this has been noted by Katsoulacos and Xepapadeas (1996a,b)). Furthermore, from (9), it is evident that the higher the emissions tax the more firms would wish to do abatement, *ceteris paribus*.

Regulator's Choice of R&D Subsidy

In the first stage, the regulator chooses the R&D subsidy, s, to maximise total welfare. Total welfare in the present setting consists of the (unweighted) sum of consumer surplus, firms' profits and environmental damages. Recall that the regulator is constrained to treat the emissions tax as exogenous, i.e. beyond its control (this choice was justified in the context of having environmental policy set at a national or supra-national level). The regulator thus solves

$$\max_{s} \int_{0}^{2q_s^*} (a-x)dx - 2[c-(1+\beta)z_s^*]q_s^* - \gamma z_s^{*2} - w_s^{*2} - \tfrac{1}{2}d(2q_s^* - 2w_s^*)^2$$

which is equivalent to:

$$\max_{s}[2Aq_s^* - 2q_s^{*2} + 2(1+\beta)z_s^* q_s^* - \gamma z_s^{*2} - w_s^{*2} - 2d(q_s^* - w_s^*)^2] \tag{11}$$

Substituting output, R&D and abatement level from (7), (6) and (9) respectively and then solving the associated first-order condition, we obtain the optimal subsidy[8]:

$$s^* = \frac{6\gamma[\beta(3-d)-d] + \tau[9\gamma(1-\beta) + 24\gamma(1+\beta)d - 2(2-\beta)(1+\beta)^2(1+2d)]}{3\gamma(1+\beta)[\tau(8d-1) + 2(2-d)]} \tag{12}$$

where $\tau \equiv t/A$ and $0 \leq \tau < 1$ given our assumption that $t < A$. Note that τ is the level of the emission tax relative to market size. It can be checked (see Appendix) that $\frac{ds^*}{d\tau} > 0$, i.e. as the emission tax increases, the optimal subsidy is higher. If the environmental policy is strict, there is less need for the regulator to correct for the environmental externalities caused by the firms' expansion of output through the industry-specific R&D subsidies.

Given the optimal subsidy, s^*, we obtain the equilibrium values for R&D, output and abatement effort:

$$z^* = \frac{A(1+\beta)[2(2-d) + \tau(8d-1)]}{\Delta} \tag{13}$$

$$q^* = \frac{A[3\gamma(1-\tau) + \tau(1+\beta)^2(2d+1)]}{\Delta} \tag{14}$$

$$w^* = \tau A \tag{15}$$

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[8] Note that setting $s = 0$ in (11) this case collapses to no technology policy case with independent R&D. By the optimality of s^* it is clear total welfare in the case of s = 0 is below total welfare with the optimal subsidy.

where $\Delta = [9\gamma - 2(1+\beta)^2(2-d)] > 0$ and all equilibrium values are positive given our assumptions on γ and d. Notice that it is easy to show that $q^* - w^* > 0$. Using (12)-(15) we obtain social welfare under optimal subsidization:

$$TW_s = \frac{A^2\{2\gamma(2-\tau) - \tau^2[11\gamma - 5(1+\beta)^2] + 2d[\gamma(8\tau - 1) - \tau^2[16\gamma - 5(1+\beta)^2]]\}}{9\gamma - 2(1+\beta)^2(2-d)} \tag{16}$$

We now proceed to examine in detail the optimal subsidy given in (12). Note first that if $d = t = 0$, i.e. if there are no environmental damages and the emission tax is set at zero, the optimal subsidy is, $s^* = \frac{3\beta}{2(1+\beta)}$. This is the standard case where the regulator, with the use of a unique policy tool (the R&D subsidy), tries to correct three market failures: the under-valuation effect, the strategic over-investment effect and the spillover under-investment effect (see e.g. Katsoulacos and Ulph (1999)). In our non-tournament model, the optimal subsidy in the absence of environmental damages is always positive and, as expected, increasing in the spillover parameter.

Suppose next that there is no environmental policy in operation,[9] i.e. $t = 0$. However, production generates pollution as a by-product, that is, $d > 0$. In this case there is a fourth market failure due to the environmental externalities that the firms generate and do not internalize through their market conduct. The optimal subsidy is then, $s^* = \frac{\beta(3-d) - d}{(1+\beta)(2-d)}$. It is easy to see that the optimal subsidy is positive if the steepness of the environmental damage function is small enough, i.e. if $d < \frac{3\beta}{1+\beta} \equiv d_{cr}$. Otherwise, a tax on R&D expenditures is optimal. In the absence

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[9] For the case of no, or loose, environmental policy we provide the following examples. The highly concentrated oil refinery in Greece has enjoyed major gains in productive efficiency and has expanded output due, greatly, to technology policy measures encouraging innovation. At the same time there is no clear environmental policy to regulate this particular industry. The same is true, to a lesser extent, for the Greek food industry. In addition, firms in the agriculture and milking industries in Spain receive both national and EU aid, usually in the form of subsidies, to promote the use of efficient productive practices without a concurrent interest or policy measure for the environmental effect of these practices. Implementing these more efficient practices can have a considerable negative impact on the environment, e.g. use of pesticides, associated with a considerable increase in production.

of environmental policy, as the damage on the environment increases, the regulator gives less incentive to firms to spend on cost-reducing R&D. In particular, if the damage function is quite steep, the regulator imposes a tax on firms' R&D activities in order to ameliorate the environmental damages resulting from the increased production due to the firms' over-investment in R&D. Of course, the critical value of d depends on the spillover parameter and, in fact, increases with β. Note that if there are no spillovers in the industry, the optimal policy is always a tax on R&D spending. This is due to the fact that the strategic over-investment effect dominates the under-valuation effect, and thus firms cause excess environmental damages due to their production expansion resulting from the firms' overinvestment in R&D.

Finally, if there is environmental policy in operation, i.e. $t>0$, the optimal subsidy is described in the following proposition.[10]

Proposition 1. *For* $0 \leq d < 2$ *and* $\gamma > 16/9$ *and given an exogenous emissions tax, t, we have the following:*

(i) For $\beta = 0$*, there exists a critical value for the emissions tax,* $\bar{t}$*, such that* $s^* < 0$ *if and only if* $t < \bar{t}$ *and* $s^* \geq 0$ *if and only if* $t \geq \bar{t}$*.*

(ii) For $\beta \in (0,1]$*, if* $0 \leq d \leq \frac{3\beta}{1+\beta} < 2$*,* $s^* \geq 0$ *while if* $0 < \frac{3\beta}{1+\beta} \leq d < 2$ *there exists a critical value* $\bar{t}$ *such that* $s^* \geq 0$ *if and only if* $t \geq \bar{t}$ *and* $s^* < 0$ *if and only if* $t < \bar{t}$*. The critical value,* $\bar{t}$*, is given by* $\bar{t} = \dfrac{6A[d-\beta(3-d)]\gamma}{3\gamma[3(1-\beta)+8d(1+\beta)]-2(2d+1)(2-\beta)(1+\beta)^2}$ *with* $\bar{t}$ *increasing in* d *and decreasing in* β*.*

Our intuition for Proposition 1 is as follows: When the spillover parameter is zero, the spillover under-investment effect is not present so that the regulator (or government) need only be concerned with the environmental externality. In the case where the emissions tax has been set at a relatively low level, the regulator will try to address the pollution problem by taxing R&D so that firms do not expand output too much as a result of cost-reducing R&D. In the opposite case, where the emissions tax has been fixed at a relatively high level the regulator will subsidise R&D (part (i) of proposition). However, when the spillover is positive, there is an inter-play between the spillover under-investment effect and the environmental externality. In the case where the environmental damage is relatively contained a subsidy to R&D is optimal for any value of the exogenous emissions tax. In contrast, when the environmental damage is relatively large, whether a tax on R&D or a subsidy to R&D is optimal depends on whether the emissions tax has been fixed at a low or high rate respectively (part (ii) of proposition). Figure 1 illustrates the content of proposition 1.

[Figure 1]

In contrast to the literature on R&D subsidies, which does not take into account the environmental dimension of an R&D-induced output expansion, we provide a clear classification identifying conditions on the spillover rate and the environmental parameter, *d*, such that R&D should be taxed or subsidised. A tax on R&D is optimal when the damage on the environment from increased production is quite substantial and the exogenous emissions tax is set at too low a rate.

2.2 Cooperative R&D

In this section technology policy takes the form of encouraging R&D by allowing firms to cooperate at the R&D stage only.[11] In the context of the present model, R&D cooperation means that firms set their R&D cooperatively to maximise joint first-stage profits while competing in the second stage, i.e. we consider a Research Joint Venture (RJV). Moreover, we

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[10] All proofs are in the Appendix.

assume that within the RJV there is full information sharing of research results or, equivalently, that the spillover is set at its maximal value.[12] We keep the exposition brief as the model presented here is very similar to the one used by Poyago-Theotoky (1995) (with $n = 2$) and refer the reader to that paper.

The output stage is the same as for the case of R&D subsidies. Thus, the optimal output and profits are given by (3) and (4) respectively, with $s = 0$ and $\beta = 1$, i.e. no R&D subsidies and the spillover parameter set at its maximum value (full disclosure of information). The difference lies in the R&D stage of this game where the objective function of the RJV is written as

$$\Pi_{RJV} = (\hat{\pi}_1 + \hat{\pi}_2) = \hat{q}_1^2 + \hat{q}_2^2 - \sum_{i=1}^{2} \frac{\gamma z_i^2}{2} + t\sum_{i=1}^{2} w_i - \tfrac{1}{2}\sum_{i=1}^{2} w_i^2 \qquad (17)$$

The first order conditions for the maximization of (17) are $\partial\Pi_{RJV}/\partial z_1 = 0 = \partial\Pi_{RJV}/\partial z_2$.[13] Solving for the symmetric equilibrium, $z_i = z_j = z_c$ we obtain

$$z_c = \frac{4(A-t)}{9\gamma - 8} = \frac{4A(1-\tau)}{9\gamma - 8} \qquad (18)$$

Given the symmetric solution, it seems reasonable to assume an equal split of profits, so that equilibrium profit per firm and output per firm are

$$\pi_c = \frac{\gamma A^2(1-\tau)^2}{9\gamma - 8} + \tau A w_i - \tfrac{1}{2} w_i^2 \quad \text{and} \qquad q_c = \frac{3\gamma A(1-\tau)}{9\gamma - 8}. \qquad (19)$$

The abatement selection stage is the same as for the previous case; firms choose their abatement effort independently and the optimal abatement effort is given by expression (9), i.e. $w_c = \tau A$. We can then write equilibrium profits per firm as

$$\pi_{i,RJV} = A^2\left[\frac{\gamma(1-\tau)^2}{9\gamma - 8} + \frac{\tau^2}{2}\right]$$

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[11] On R&D cooperation see, e.g. Jacquemin (1988), Kamien, Mueller and Zang (1992), Vonortas (1994) and Poyago-Theotoky (1995).

[12] The majority of papers on R&D cooperation make this assumption on the spillover in the RJV; e.g. see Beath et. al (1998). Note that this choice can be justified if one treats the spillover as a choice variable suitably reinterpreted as disclosure rate. It can be shown that it is optimal for an RJV to set $\beta = 1$ (Poyago-Theotoky (1999)).

and all equilibrium values are positive given our assumptions on γ and d. The next step in our analysis consists in calculating total welfare, where

$$TW_{RJV} = 2Aq_c - 2q_c^2 + 4q_c z_c - \gamma z_c^2 - w_c^2 - 2d(q_c - w_c)^2 \tag{20}$$

which, upon performing the necessary substitutions and some algebraic manipulation results in

$$TW_{RJV} = \frac{A^2\{4\gamma(9\gamma-4) - 2\gamma(9\gamma+8)\tau + \tau^2[11\gamma(16-9\gamma)-64] - 2d[(12\gamma-8)\tau - 3\gamma]^2\}}{(9\gamma-8)^2} \tag{21}$$

We next proceed in comparing social welfare under the two variants of technology policy, i.e. compare expressions (16) and (21).[14]

2.3 Welfare comparison

Having discussed the conditions for the optimal R&D subsidy/tax we are now in a position to examine the welfare consequences of the two different policies. The results concerning the comparison between social welfare in the case of R&D subsidization and social welfare in the case of R&D cooperation are summarised in the next proposition.

Proposition 2. *Given* $0 \leq d < 2$, $\gamma > 16/9$ *and an exogenous emissions tax,* $t = \tau A$*:*

(i) *If the environmental policy is loose enough, i.e.* τ *is sufficiently small, then there exists a critical value of d,* $\bar{d}(\gamma)$*, with* $\partial \bar{d} / \partial \gamma > 0$*, such that if* $d > \bar{d}(\gamma)$ *then* $TW_s > TW_{RJV}$*; otherwise, for lower values of d, there exists a critical value of* β*,* $\bar{\beta}(d)$*, such that if* $\beta \geq \bar{\beta}$ *then* $TW_s > TW_{RJV}$ *and if* $\beta < \bar{\beta}$*,* $0 \leq \bar{\beta}(d) < 1$.

(ii) *On the other hand, if the environmental policy is strict enough, for all d, there exists a critical value of* β*,* $\bar{\beta}(d)$*, such that if* $\beta \geq \bar{\beta}$ *then* $TW_s > TW_{RJV}$ *and if* $\beta < \bar{\beta}$*,* $0 \leq \bar{\beta}(d) < 1$.

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[13] The second order and stability conditions are satisfied.

Proposition 2 identifies conditions on the spillover parameter, β, and the slope of the marginal damage function, *d*, such that welfare in the presence of R&D subsidies is higher (lower) than welfare when there is an RJV. In the most interesting case where the environmental policy is rather loose, the R&D subsidization leads always to higher welfare than the encouragement of RJVs whenever the environmental damages are severe (for high values of *d*). The regulator can partially correct for the environmental externality by properly adjusting its level of R&D subsidy (or by even imposing an R&D tax), while this is not possible if the regulator simply encourages cooperative R&D. R&D subsidization also does better in terms of welfare than an RJV in the case where the environmental damages are less severe, or the environmental policy is strict enough, but only if there is a serious under-investment effect due to high spillovers ($\beta > \overline{\beta}$). When the spillover value is high, the full information sharing that occurs in an RJV differs very little from the situation where firms almost fully enjoy each other's innovations. As previously, the regulator through the encouragement of an RJV cannot correct for the environmental externality, while it can do so by appropriately adjusting its level of R&D subsidy.

On the other hand, for spillover values below the critical value, $\overline{\beta}$, the RJV results in higher welfare, provided that the environmental policy is strict enough. When R&D is done cooperatively and there is full information sharing, i.e. the spillover parameter is set at its maximal value, firms reduce their R&D spending and thus save on R&D costs and also decrease their emissions. As the level of pollution and the firms' R&D expenditures are lower than when R&D is subsidized, total welfare is higher in an RJV.

We conclude that there is a relatively wide class of cases where a policy of R&D subsidisation performs better than a policy of encouraging R&D. Figure 2 provides a specific

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[14] We do not provide a detailed comparison of R&D, output and profit per firm as this is outside the scope of the

illustration of Proposition 2. Following this result, for the rest of this paper we concentrate on the case of R&D subsidies, and examine whether it is possible to induce firms to undertake additional abatement effort in an attempt to improve social welfare further.

[Figure 2]

3. Conditional R&D Subsidisation Contracts

Recall that the regulator/government is constrained in its choice of instrument to deal with the environmental damage problem given that the emissions tax is exogenous. This means that if the regulator wishes to address the pollution problem further, it has to use the only available instrument, that is the R&D subsidy, if by doing so welfare can be increased above the level identified by expression (16). We thus consider tying-in technology policy instruments to abatement effort in order to deal with the negative pollution externality. From proposition 1 we know that in a number of cases the optimal policy is a tax on R&D; in these cases we cannot consider tie-in policies as it makes no sense to combine a tax on R&D with a requirement that firms spend more on abatement. However, in cases where the optimal policy is a subsidy towards R&D we can examine the option of R&D subsidy contracts conditional on abatement effort.

In this instance we propose a specific and novel policy scheme in the form of a conditional R&D subsidy, given only if firms spend a minimum acceptable amount on abatement (above the level identified by (15), the independently chosen abatement level). Figure 1 provides a specific illustration of the parameter space where the tie-in policy can be implemented. In particular, the policy scheme consists in providing a *subsidy s on R&D costs if* $w_i \geq \hat{w}$*; otherwise, no subsidy*, where $\hat{w}$ is the critical level of abatement (to be defined later).[15] Obviously, this non-linear R&D subsidy contract gives more flexibility to the regulator and she can thus achieve at least the same level of welfare as with the optimal R&D subsidy. In fact, the

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present paper.

[15] The policy takes the form of a threshold-contract.

optimal R&D subsidy is a special case of the tie-in policy where the critical abatement level has been set equal to 0. As is shown below, the regulator achieves a higher level of welfare by offering R&D subsidies conditional on firms' investing in abatement well above their individual profit-maximizing abatement level.

The purpose of the tie-in R&D subsidy scheme is to give incentives for cost-reducing innovation only as long as firms spend on abatement some specified amount. Under the proposed policy a firm faces the following cost structure in addition to the constant unit costs of production and the exogenous emissions-tax burden:

$$\begin{cases} (1-s)(\gamma z_i^2/2) + w_i^2/2 & \text{if } w_i \geq \hat{w} \\ \gamma z_i^2/2 + w_i^2/2 & \text{otherwise} \end{cases}$$

In order to proceed, rewrite social welfare in the case of R&D subsidies as

$$TW_s = [2Aq_s^* + 2(1+\beta)z_s^* q_s^* - 2q_s^{*2} - \gamma z_s^{*2}] - w^2 - 2d(q_s^* - w)^2 \tag{22}$$

Note that in (22) it is implicitly assumed that abatement expenditures, *w*, will be the same for the two (ex-ante symmetric) firms. This is reasonable, as firms have no incentive to spend on abatement more than the threshold level required for them to receive the R&D subsidy, provided that the threshold level of abatement is higher than w^* (see (9)). Since from (6) and (7), $\frac{dq_s^*}{dw} = 0 = \frac{dz_s^*}{dw}$, solving the first-order conditions of (22) with respect to *w* and *s* we get the optimal abatement level and the optimal subsidy

$$\hat{w} = \frac{2Ad[3\gamma(1-\tau) + \tau(1+\beta)^2]}{9\gamma(1+2d) - 2(1+\beta)^2(2+3d)} > \tau A = w^* \tag{23}$$

$$\hat{s} = \frac{6\gamma(3\beta - d + 5\beta d) + \tau[9\gamma(1-\beta) + 12\gamma(2-\beta)d - 2(1+2d)(2-\beta)(1+\beta)^2]}{3(1+\beta)\gamma(4+6d-\tau)} > 0 \tag{24}$$

As expected, the optimal abatement $\hat{w}$ is higher than the individual firm's profit maximizing abatement effort w^*. Firms, while selecting their abatement effort, do not take into account the negative externality that they cause on the environment. Their decision is based only on their marginal tax savings due to the reduction of emissions resulting from their abatement effort. Since the regulator can partially correct the environmental externality problem via the requirement that firms must spent more on abatement in order to receive the R&D subsidy, there is less need now for the regulator to address the pollution problem by adjusting downwards its R&D subsidy level. As a result, the optimal subsidy in the tie-in policy, $\hat{s}$, is higher than the optimal subsidy, s^*, under the standard scenario.[16] This is an important advantage of the proposed scheme. Under the conditional R&D subsidization scheme, firms are given stronger incentives to invest in cost-reducing R&D, while at the same time, the environmental damage caused through the expansion of their output is addressed via the requirement that firms have to spend a minimum amount on abatement.

In particular, from (23) notice that in the case where the (exogenous) emissions tax is set at (or close to) zero, i.e. no (or loose) environmental policy, firms will now undertake abatement whereas in the absence of the tied-in policy no abatement would be undertaken. Moreover, from (24) it can be easily checked that the optimal (conditional on abatement) subsidy is higher than the optimal subsidy in the absence of tie-in policy in case that there is no environmental policy in operation. The main result of this section is summarised in the following proposition.[17]

Proposition 3. *In the case of non-cooperative R&D, a policy of a tied-in R&D subsidy taking the form "provide a subsidy $\hat{s}$ on R&D costs if $w_i \geq \hat{w}$, where $\hat{w}$ and $\hat{s}$ are given by (23) and*

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[16] This can be checked comparing (24) to (12). As this comparison is tedious and does not add much to our analysis, it has not been included in the paper. It is, however, available from the authors upon request.

[17] We have assumed that the relevant participation constraint is satisfied, i.e. a firm has an incentive to undertake additional abatement and receive the R&D subsidy as its profits in this case exceed the profits from not receiving the subsidy and doing the minimal abatement. If the participation constraint is not satisfied, i.e $\pi_S(\hat{w}) < \pi_i$, in order to force firms undertake additional abatement a lump sum T can be given to restore incentives, $\pi_S(\hat{w}) + T = \pi_i$, where π_i is the equilibrium profit when $s = 0$.

(24); otherwise, provide no subsidy", is an optimal policy which is welfare improvement, in a second-best sense.

The essence of proposition 3 consists in that it identifies a technology policy contract in the form of a tied-in R&D subsidy that, in addition, aims to improve upon the environmental damage associated with the output expansion caused by the cost-reducing R&D. Our analysis has shown that spending on R&D and obtaining a subsidy can have beneficial side effects on the environment through firm's increased abatement activities. That is, the R&D subsidy can also help in pollution control without being targeted directly on abatement effort. The R&D subsidy can thus have a dual role: to correct partly the R&D underinvestment problem - due to the market failure caused by the spillover under-investment effect, and to encourage pollution control through abatement activities thus aiming at the market failure associated with the environmental externality.

We should note here that an alternative tying-in policy could take the form of allowing R&D cooperation - in the absence of any R&D subsidies- only if additional abatement expenditures are undertaken.[18] This latter policy can be shown to improve welfare as well. However, it seems questionable whether such a policy can be easily enforced and/or monitored and is not pursued any further.

4. Concluding Remarks

In this paper we have studied a hitherto neglected aspect of technology policy resulting from the adverse impact that such policy might have on the environment through an output expansion effect due to firm's cost-reducing activities. In the limited context of our analysis, where the emissions tax is exogenous, irrespective of whether technology policy takes the form of R&D subsidies or the encouragement of Research Joint Ventures (RJVs), R&D leads to increased pollution and thus a negative impact on the environment. As a result, policies that might have been optimal in the absence of any environmental side-effects cease to be so. In particular, we have identified conditions on the spillover and environmental parameters under which the optimal R&D subsidy becomes negative, i.e. an R&D tax. Comparing social welfare in the two different technology policy set-ups under consideration, i.e. pre-competitive R&D cooperation and R&D subsidization, we have found that such comparisons hinge on the relative magnitudes of the spillover rate and the steepness of the marginal environmental damage function. For a wide class of cases, R&D subsidisation has resulted in higher social welfare relative to R&D cooperation. As a way to improve social welfare, we have proposed a novel policy that consists in tying-in the R&D subsidy to abatement effort. We have shown that the specific policy of using a targeted subsidy on R&D costs provided that a minimum critical amount of abatement is undertaken by firms, results in a clear improvement in social welfare leading firms to invest in the optimal abatement level (in a second-best sense). The targeted R&D subsidy can be seen as having a dual role: it corrects partly R&D underinvestment, which results from the appropriability problem, and it also alleviates the pollution problem.

While our results have been obtained within a limited model we do not believe that they are model-specific. Our analysis indicates that: (1) when the environmental impact of technology policy is taken into account policies that might be optimal in the absence of an environmental dimension cease to be so and (2) the comparison between different policies becomes a delicate matter, an aspect which is not usually considered in the industrial organisation literature. We believe that the importance of our results goes beyond the specific model used. At the very least they show that the issue we have touched upon deserves further investigation.

There are a number of dimensions in which this research line can be extended. First, one could consider a policy that allows RJVs as long as a certain share of the R&D budget of the RJV is spent on abatement activities, in the absence of R&D subsidies. This opens up the

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[18] An analysis of this policy can be obtained from the authors upon request.

possibility of R&D specialisation by the cooperating firms provided that information-sharing takes place within the RJV. This type of policy could induce complementary research projects, which would benefit the RJV partners. Second, asymmetric or differential subsidies could be examined. For example, within an RJV, one of the partners could receive a subsidy on cost-reducing innovation while the other receives a subsidy on abatement. Of course, this latter option would entail coordination issues between the partners and might also require a maximum of emissions imposed on each firm.

APPENDIX

Proof of Proposition 1

From expression (12) giving the optimal subsidy, s^*, we obtain

$$\frac{\partial s^*}{\partial t}=\frac{\partial s^*}{\partial \tau}\frac{\partial \tau}{\partial t}=A\frac{2(2-\beta)(2d+1)[9\gamma-2(1+\beta)^2(2-d)]}{3\gamma(1+\beta)[-4+\tau-d(2-8\tau)]^2}>0$$

i.e. higher values for the exogenous emissions tax call for an increase in the optimal subsidy, s^*.

Next, setting $t = 0$, which implies $\tau=0$ and using (12), $s^*\big|_{\tau=0}>(<)0$ for $\frac{3\beta}{1+\beta}>(<)d$. Given the assumption that $0\le d<2$, we have:

(i) for $\beta=0$, $s^*\big|_{\tau=0}<0$ and combining this with $\frac{\partial s^*}{\partial t}>0$ guarantees that there exists a critical value for the exogenous tax, $\bar{t}$, where $\bar{t}\equiv\{\tau\,|\,s^*=0\}$, such that for $t<\bar{t}$, $s^*<0$ (i.e. impose a tax on R&D) whereas for $t\ge\bar{t}$, $s^*\ge 0$ (i.e. provide a subsidy to R&D);

(ii) for $\beta\in(0,1]$ note that first, $s^*\big|_{\tau=0}>0$ when $0\le d\le\frac{3\beta}{1+\beta}<2$ so that combining this with $\frac{\partial s^*}{\partial t}>0$ results in $s^*\ge 0$ (i.e. providing a subsidy to R&D) for any exogenous emissions tax, t and second, $s^*\big|_{\tau=0}<0$ when $0<\frac{3\beta}{1+\beta}\le d<2$, so that combining with $\frac{\partial s^*}{\partial t}>0$ guarantees that there exists a critical value for the exogenous tax, $\bar{t}$, where $\bar{t}\equiv\{\tau\,|\,s^*=0\}$, such that for $t<\bar{t}$, $s^*<0$ and for $t\ge\bar{t}$, $s^*\ge 0$.

The critical value, $\bar{t}$, is found from (12) and is given by

$\bar{t}=\frac{6A[d-\beta(3-d)]\gamma}{3\gamma[3(1-\beta)+8d(1+\beta)]-2(2d+1)(2-\beta)(1+\beta)^2}$. Finally, it can be checked that $\bar{t}$ is increasing in d and decreasing in β. Q.E.D.

Proof of Proposition 2

Note that $TW_s \geq TW_{RJV}$ if the following inequality holds

$$\frac{[2\gamma(2-\tau)-[11\gamma-5(1+\beta)^2]\tau^2+2d[\gamma(8\tau-1)-\tau^2(16\gamma-5(1+\beta)^2)]]}{9\gamma-2(1+\beta)^2(2-d)} \geq$$

$$\frac{[4\gamma(9\gamma-4)-2\gamma(9\gamma+8)\tau+[11\gamma(16-9\gamma)-64]\tau^2-2d[(12\gamma-8)\tau-3\gamma]^2]}{(9\gamma-8)^2} \qquad \text{(A1)}$$

Let $b=(1+\beta)^2$. This gives two solutions for β one of which is negative and thus is discarded. The other solution is given by $\bar{\beta}$ where $\bar{\beta} \equiv \{\beta \mid TW_s = TW_{RJV}\}$ and $\bar{\beta} = f(d, \gamma, \tau)$.[19] It is possible although tedious to show that $\bar{\beta} < 1$. (A1) is satisfied for $\beta \geq \bar{\beta}$, while the opposite is true, i.e. $TW_{RJV} > TW_s$ for $\beta < \bar{\beta}$. Q.E.D.

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[19] The exact solution is available from the authors upon request.

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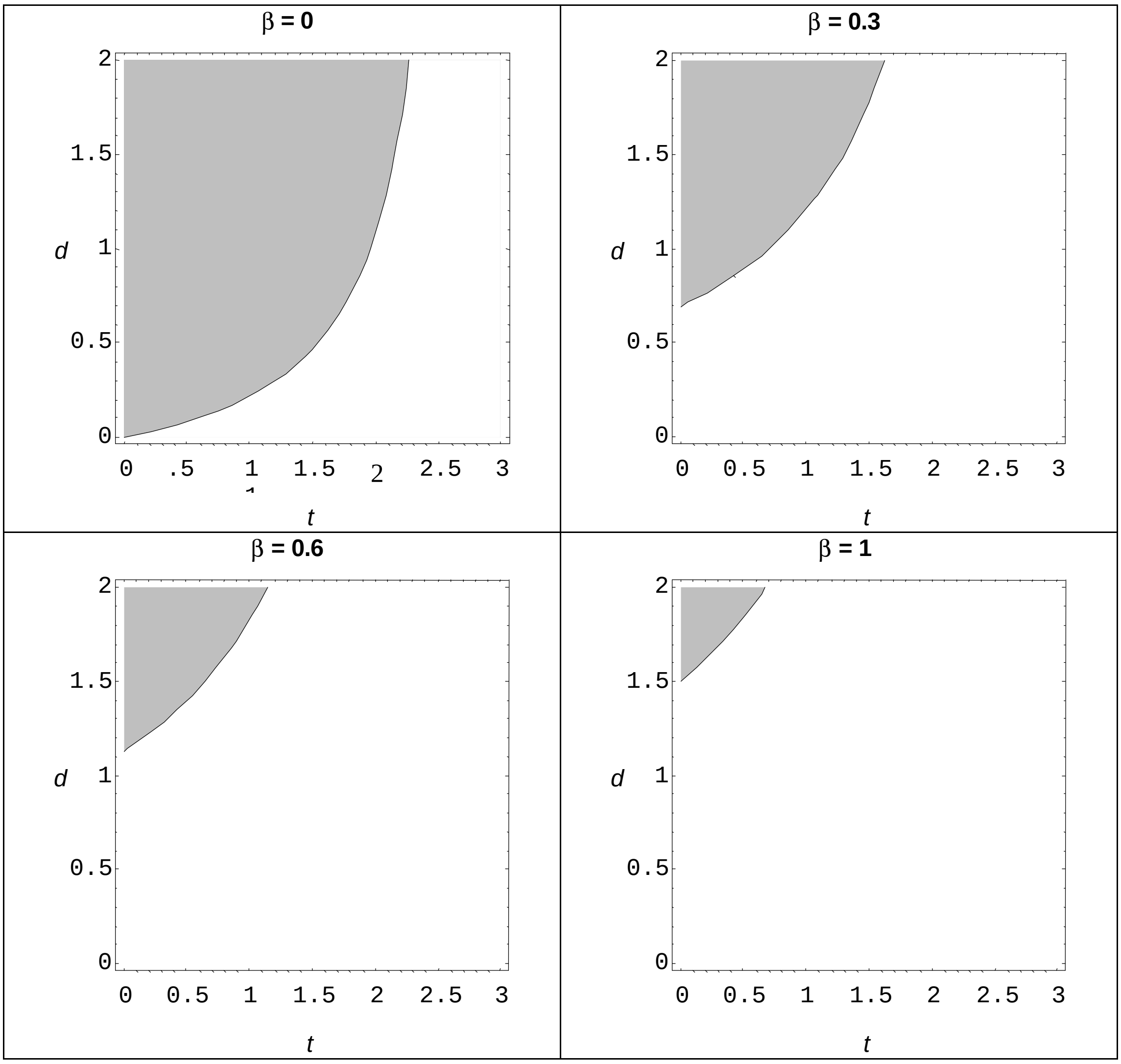
Figure 1

The Optimal R&D Subsidy/Tax

($A=10, \gamma = 5$)

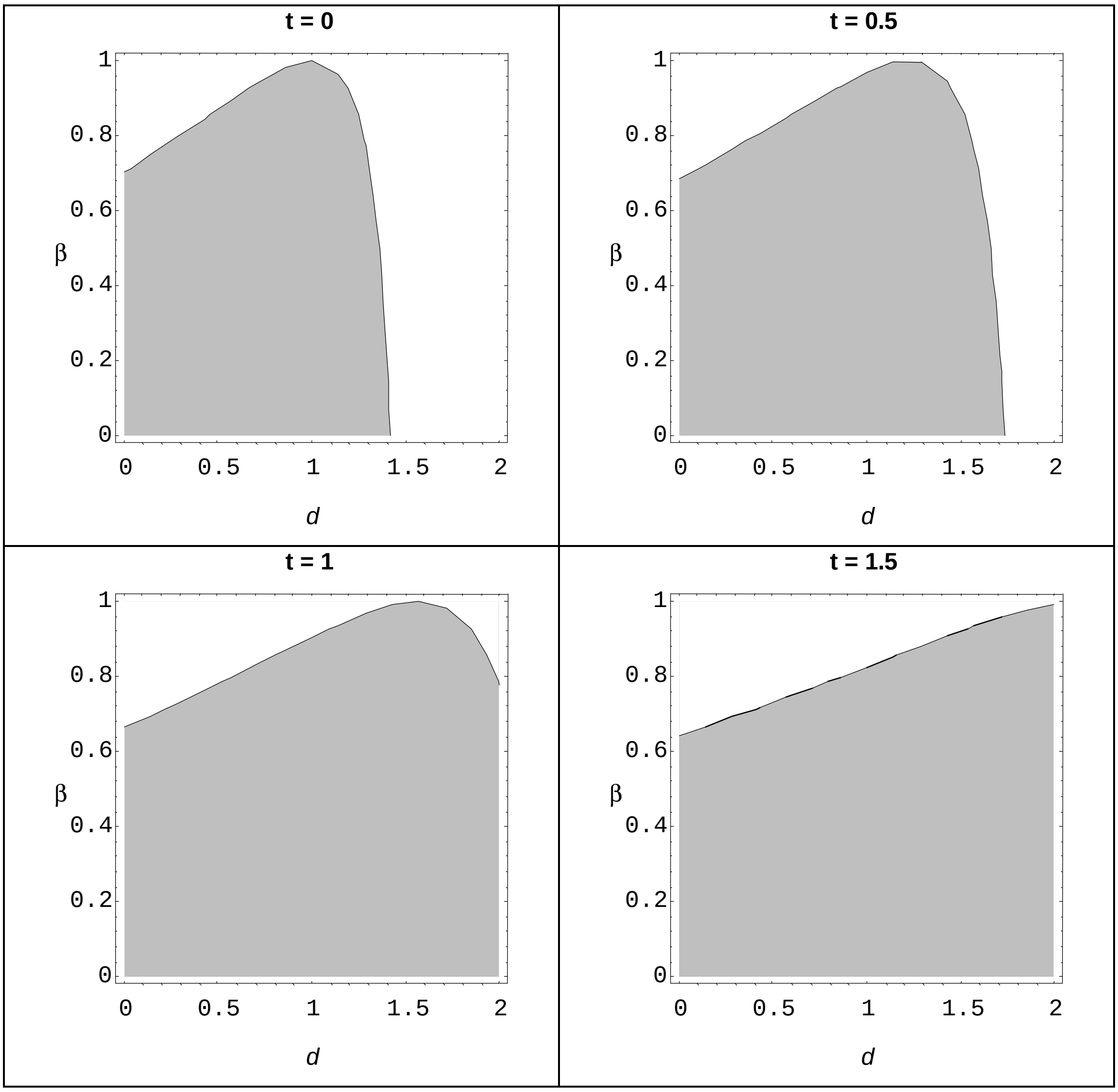


Note: In the shaded areas a tax on R&D is optimal, in the white areas a subsidy towards R&D is optimal. β is the spillover rate, d is the marginal damage parameter, t is the exogenous emissions tax, A is a measure of market size and γ is the R&D efficiency parameter.

Figure 2

Welfare Difference Contours at *Wdiff* = 0, *Wdiff* = $TW_{sub} - TW_{rjv}$

(A = 10, γ = 5)

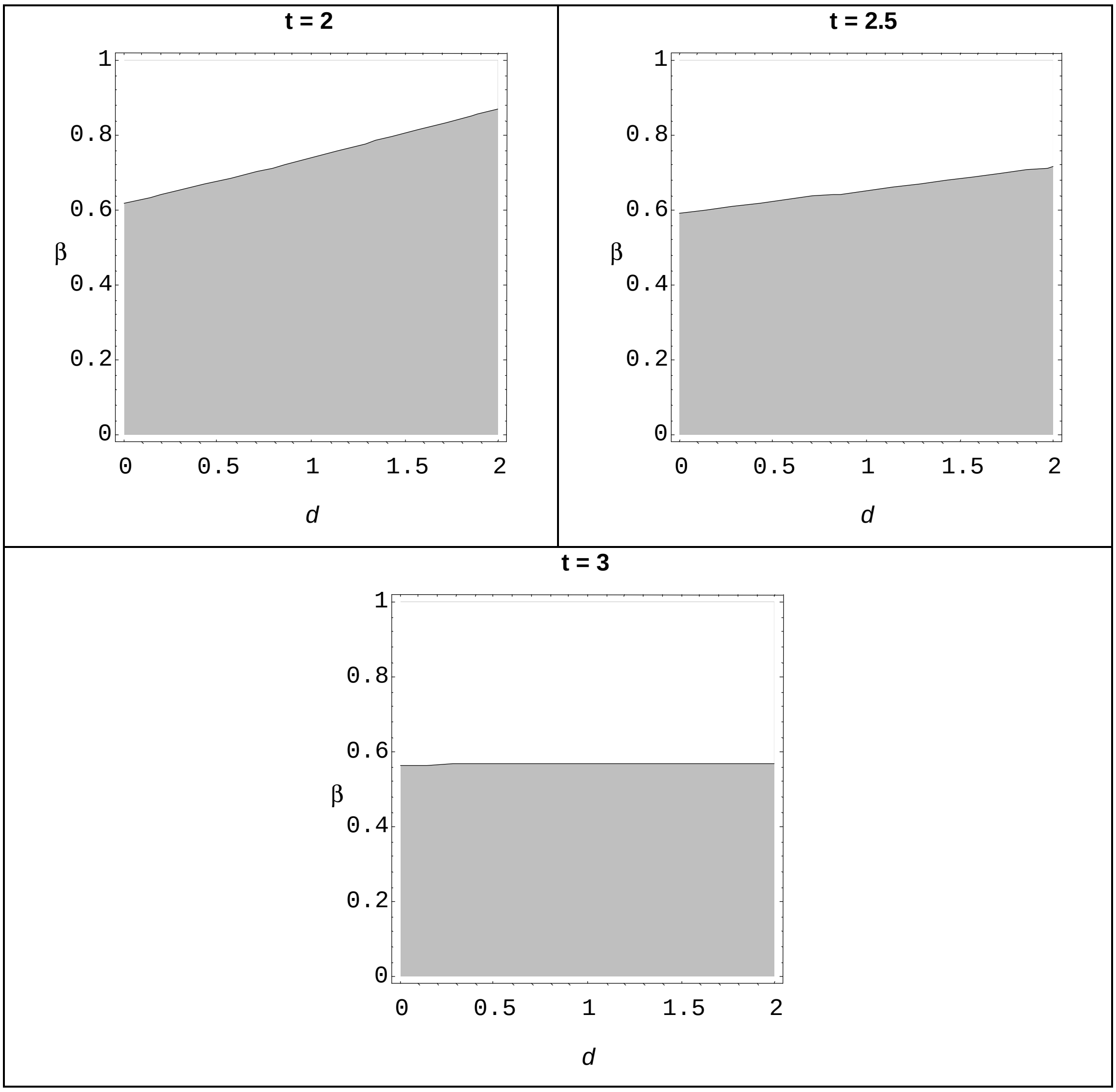


Note: In the shaded areas R&D cooperation yields higher welfare and in the white areas R&D subsidisation results in higher welfare. β is the spillover rate, *d* is the marginal damage parameter, *t* is the exogenous emissions tax, *A* is the size of the market parameter, γ is the R&D efficiency parameter.

Figure 2 (cont.)

Welfare Difference Contours at $Wdiff = 0$, $Wdiff = TW_{sub} - TW_{rjv}$

($A = 10$, $\gamma = 5$)



Note: In the shaded areas R&D cooperation yields higher welfare and in the white areas R&D subsidisation results in higher welfare. β is the spillover rate, *d* is the marginal damage parameter, *t* is the exogenous emissions tax, *A* is the size of the market parameter, γ is the R&D efficiency parameter.