NBER WORKING PAPER SERIES

THE EFFECTS OF ENVIRONMENTAL POLICY ON THE PERFORMANCE OF ENVIRONMENTAL RJVS

Yannis Katsoulacos
Alistair Ulph
David Ulph

Working Paper 7301
http://www.nber.org/papers/w7301

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
August 1999

An earlier version of this paper was presented at the joint FEEM/NBER Conference “Distributional and Behavioral Effects of Environmental Policy,” June 11-12, 1999. We are grateful for the insightful comments received from our discussant Jerome Rothenberg and from Gib Metcalf, Carlo Carraro, Sjak Smulders, John Whalley, and other participants at the conference. The views expressed herein are those of the authors and not necessarily those of the National Bureau of Economic Research.

The Effects of Environmental Policy on the
Performance of Environmental RJVs
Yannis Katsoulacos, Alistair Ulph, and David Ulph
NBER Working Paper No. 7301
August 1999

ABSTRACT

Much of the potential impact of environmental policy is though to come from the incentives it gives firms to develop and introduce new environmental products and processes. Almost all the literature on this issue has focused on the impact of environmental policy on the amount environmental R&D that firms undertake, assuming that such R&D is undertaken independently or non-cooperatively. It is now widely recognized that there are considerable potential benefits from having firms undertake R&D cooperatively through research joint ventures (RJVs). In this paper we analyze the impact of environmental policy on the performance of environmental RJVs and underage an explicit welfare comparison of this performance against the counterfactual of a non-cooperative equilibrium. The framework we adopt is that developed by Katsoulacos and Ulph (1998) which identifies three stages in the innovative process -- research design, R&D; information sharing -- and endogenises each of these inter-related decisions in both the cooperative and non-cooperative equilibria. The case we examine is that in which governments cannot commit to environmental policy, so all these decisions have to taken anticipating the environmental policy that will finally be imposed. We show that RJVs are welfare enhancing when the levels of environmental damage caused by pollution are low. In this case RJVs fully share information and internalize the associated externality. However when the level of damage is high, it turns out that firms anticipate tougher environmental policy when they share information then when they do not, and so do not share information. This distorts the RJV's R&D decisions in ways that make the non-cooperative equilibrium welfare enhancing.

Yannis Katsoulacos
Athens University of Economics and Business
76, Patission Street
Athens 104 34
Greece

Alistair Ulph
University of Southampton
Highfield, Southampton SO17 1BJ
United Kingdom

David Ulph
University College London
Gower Street
London WC1E 6BT
England

The Effects of Environmental Policy on the Performance of Environmental RJVs

Over the last ten years a significant literature has developed on the effects of environmental policy on the incentives of firms to undertake R&D that will lead to the development of new environmentally friendly products and/or processes. In what follows we refer to this as environmental R&D.

The starting point of this literature is the recognition that market forces will produce very weak incentives for firms to undertake environmental R&D, and so government incentives are required to correct this market failure. There have been three main strands in this literature.

(a) The first[1] examines the effects of environmental policy – e.g. taxes, standards – on the incentives to undertake R&D. An important point that emerges from this literature is that while environmental policy does indeed give firms an incentive to undertake environmental R&D, a toughening of this policy will not necessarily increase the amount of R&D. For while a tougher environmental policy will have a direct effect of encouraging more environmental R&D, it can also have the indirect effect of raising costs, reducing output, and this will lower R&D incentives. Thus, contrary to the widely discussed Porter Hypothesis, there is no theoretical presumption that tougher environmental policy will itself be sufficient to promote greater R&D incentives.

(b) A second strand[2] looks at the combined effects of both technology policy and environmental policy on the levels of R&D, output and emissions in an oligopolistic industry. Thus, in the context of a model where firms do only environmental R&D, Katsoulacos and Xepapadeas (1996) show that a combined R&D subsidy plus emissions tax can generate the first-best. Petrakis and Poyago-Theotoky (1997) explore the design of technology policy in the context where governments are constrained in the use of environmental policy.

(c) The third strand[3] considers the setting of environmental policy in a multinational context, where governments are aware that the levels of environmental policies they set will affect the strategic competition between firms – particularly their choice of R&D. The issue here is whether trade concerns lead governments to set environmental policies that are too lax.

A feature of virtually all[4] this literature is that it assumes that firms undertake R&D in a non-cooperative fashion. However there are many potential benefits that are thought flow from having firms undertake R&D co-operatively in a research joint venture (RJV): a reduction in risk; the achievement of economies of scale and scope; the elimination of wasteful duplication; the greater appropriation of the returns to innovation. These benefits arise because RJVs are thought to promote greater information sharing and co-ordination of R&D decisions[5].

There is now a considerable literature on the performance of RJVs. However this literature focuses exclusively on the types of product and process R&D that firms undertake for conventional commercial benefit, and, as such ignores environmental innovation, which, as we pointed out above, is primarily undertaken in response to environmental policies[6]. Consequently in this paper we wish to understand how environmental policy affects environmental innovation when we allow for the possibility that this innovation is undertaken cooperatively through the formation of what we will call environmental RJVs. In particular, we wish to understand how environmental policy affects the innovative performance of RJVs as compared to a non-cooperative equilibrium.

The plan of the paper is as follows. In section 1 we set out some background discussion on the current understanding of RJV performance, and sketch out the issues that need to be addressed in thinking about the interaction between environmental policy and the performance of environmental RJVs. In section 2 we develop a formal analysis of some of the issues identified in section 1.

Before proceeding, it is important to point out that in this paper we focus on the case where the central rationale for RJVs is the avoidance of duplication in R&D. This captured by the assumption that the nature of research discoveries made by firms is duplicative. We fully recognise that an important alternative motivation of RJVs is to exploit complementarities, and in Katsoulacos and Ulph (1998) we provide a positive analysis of this case. However a full welfare analysis of this case would require a separate paper.

Section 1 Preliminaries

In thinking about the interaction between environmental policy and the performance of environmental RJVs, it is important to recognise that there are a number of market failures in operation.

(a) Product Market Failures

Taking as given the number of firms, the products they produce and the technology[7] they employ, there are two market failures that can arise in relation to firms' output decisions. The first is the conventional pollution externality, which typically leads firms to overproduce. The second is imperfect competition arising from the oligopolistic nature of markets. This in turn may be attributable to entry barriers – in particular the scale economies generated by R&D. Imperfect competition typically leads to firms producing too little output. The ability of the it is well known that in principle an emissions tax can be chosen to obtain the first-best level of output. Notice that the tax which achieves this first-best will depend on the technologies employed by the firms.

(b) Innovation Market Failures

To facilitate discussion, here *and throughout the rest of the paper* we assume that:

(i) there are only two firms;

(ii) the products that firms produce are perfect substitutes;

(iii) the research paths that firms are pursuing are perfect substitutes (or, more accurately, perfect duplicates) in the sense that if both firms make a discovery, they have discovered exactly the same thing and so cannot gain from any knowledge sharing.

The first two assumptions are made in most of the RJV literature but are by no means innocuous. The third captures one of the possible reasons why RJV forms – to avoid duplication. However it ignores another potential gain from RJV formation – exploiting research complementarities. We fully recognise the importance of this motive, and have recognised it in the positive analysis contained in Katsoulacos and Ulph (1998). However a full treatment of this case in the context of the welfare analysis we conduct here would warrant another paper.

It is well known in the industrial organisation literature that there are significant market failures in the innovation process. These stem primarily from the public good nature of knowledge, as something that is costly to produce, but virtually costless to reproduce. As is well known, this implies that the optimum allocation of resources involves having R&D undertaken in a relatively small number of labs, with the results being sold to others at a price equal to the value which society places on this knowledge. In this idealised market system firms undertaking any R&D would perceive a return equal to the value that the entire industry would place on it.

However, in the absence of any policy intervention, actual market mechanisms will not produce such an outcome. In particular, free riding on discoveries would so lower the rate of return to R&D that very little R&D would be undertaken. In the face of this market failure, virtually all governments institute a system of protection of intellectual property rights – of which the patent system is the major part.

While patents provide some correction of the fundamental market failures, they involve their own distortions, essentially because they reward firms for discovering information, but not for sharing it. To see what market failures still exist under a patent system, suppose for the moment that patents are fully effective (i.e. there are no involuntary information leakages) and that there are no mechanisms for sharing information.

To fully understand the nature of market failures, it useful to follow Ulph and Katsoulacos (1998) and distinguish three stages in innovation decisions.

(a) *Research Design* - in the case considered here, this amounts to choosing the number of labs to operate;

(b) *R&D* - choosing the amount of R&D to do in each lab;

(c) *Information Sharing* – if a lab makes a discovery, choosing the amount of information to share with the other lab.

We then know that when firms act non-cooperatively their decisions are subject to the following potential market failures[8]. Working backwards, these are

(c) At the *Information Sharing* stage firms will fail to share information when it is always socially desirable to do so.

(b) At the *R&D* stage there are three market failures:
  (i) the *undervaluation effect* - firm's base decisions on profits rather than total surplus (profits plus consumer surplus), and so do too little R&D;
  (ii) the *self-centredness effect* – firm's base decisions on the gains to themselves from having a new technology rather than the gain to the industry if everyone got the new technology; again this results in too little R&D:
  (iii) the *competition to be first effect* – firm's have incentives to try to be the first to introduce a new technology, and this leads to their over-investing in R&D:

(a) At the *Research Design* stage, there may be *excessive duplication* as each firm will operate its own lab, while it may be socially optimal to operate a single lab.

Suppose now that patents are not completely effective, and there are involuntary unpaid information leakages – spillovers. This will mitigate some of the welfare losses at the *information-sharing* stage, but will introduce a fourth distortion at the *R&D* stage, for firms acting independently will not internalise the externality arising from the spillover. We call this the *spillover effect*. It introduces a third reason why firms will underinvest in R&D.

Notice that it is not at all clear whether, on balance, firms are doing too little or too much R&D – either individually or collectively. What is clear is that a major reason why these market failures arise is that, by themselves, patents do not reward firms for sharing information. To resolve these difficulties it is therefore necessary to introduce mechanisms that reward firms for sharing information. Two widely discussed methods of doing this are (a) through licensing, and (b) through the creation of research joint ventures (RJVs).

While licensing is certainly used in certain contexts, it is NOT a general solution to all the above problems. In the first place, while it will often solve the *information sharing* problem that arises in the final stage of the decision-making process, it will not always do so. For even when there are only two firms – a buyer and a seller - a license will only be sold if the maximum amount the buyer is willing to pay exceeds the minimum amount the seller needs to receive – and this need not always be the case. More seriously, licensing will not solve the problems arising in the first two stages of innovation decision-making. In particular, it does not eradicate the *competition to be first effect.* For, instead of competing to be the first to get exclusive use of a new technology, firms compete to be the first to be able to license it.

Given these problems with licensing attention has focused recently on RJVs as a possible solution to the above market failures. RJVs are arrangements under which firms are allowed to act cooperatively over all three stages of the innovation decision-making process, but are required to compete in the product market. *Prima facie* it would seem that, by taking cooperative decisions about all aspects of innovation, RJVs could mitigate most of the market failures discussed above.

- By acting cooperatively firms may be induced to share information and so mitigate the market failure at the *information-sharing* stage.
- Turning to the R&D stage, we can see intuitively that acting cooperatively to maximise joint profits firms would (a) internalise any spillovers; (b) eliminate the *competition to be first effect*; (c) remove *the self-centredness effect*.
- Finally, turning to the *research design* stage cooperative decision-making means that firms may choose to operate a single lab rather than two independent labs.

These informal arguments suggest that the only market failure that RJVs may not potentially overcome is the *undervaluation effect*.

Given these potential benefits, it is not surprising that RJVs have received considerable attention. However when one examines the theoretical literature on the subject, it turns out that, while it has provided some useful insights, nevertheless there are a number of weaknesses in the way it typically models RJVs, and consequently the analysis fails to fully address many of the above issues[9]. The major weaknesses of this literature are as follows.

(i) Spillovers are treated as exogenous. Either spillovers are the same in the cooperative equilibrium as in the non-cooperative equilibrium or else it is assumed that they are greater in the cooperative equilibrium. In neither case does the theory *explain* how cooperation might lead to greater information sharing.

(ii) Research discoveries by firms are assumed to be perfect complements. In both the cooperative and the non-cooperative equilibrium, it is assumed that information gained from other firms just adds to the progress that a firm makes on its own. This ignores the possibility of needless duplication of research, and also that one of the benefits of an RJV is that it increases the degree of complementarity.

(iii) A related problem is that equilibria are assumed to be symmetric. In particular, in both the cooperative and the non-cooperative equilibrium all firms are active in R&D, and all do the same amount of R&D. This ignores the possible cost savings by concentrating R&D in a smaller number of labs.

(iv) The non-cooperative equilibrium is taken to be one in which no licensing is possible. Since many of the models assume that there are just two firms, it would seems sensible to allow the possibility of licensing – particularly if one wants to understand the full benefits of cooperation versus non-cooperation.

To get a sense of just how limiting these assumptions are it is worth noting the following result by Hinloopen (1998).

Result 1

Suppose we have an industry comprising *n* identical firms. In addition suppose

(i) R&D spillovers are the same in both the cooperative and the non-cooperative equilibrium;

(ii) the only policy instrument available to the government is an R&D subsidy;

(iii) R&D discoveries are perfect complements in both the cooperative and non-cooperative equilibrium;

(iv) both the cooperative and the non-cooperative equilibria are symmetric;

(v) the R&D subsidy can be financed by non-distortionary taxation.

Then the cooperative and non-cooperative R&D equilibria achieve exactly the same level of welfare.

Proof. The proof is simple. Given the assumptions, effectively the only variable that can be chosen by both firms and the social planner is the amount of R&D per firm. Work out the second-best[10] optimum level of R&D. R&D per firm will be monotonically increasing in the level of subsidy in both the cooperative and the non-cooperative equilibrium. So, whether firms act cooperatively or non-cooperatively the subsidy can always be chosen to make these equilibria coincide with the second-best optimum.

The conclusion then is that, as long as governments can subsidise R&D – which, typically, they do - then the promotion of RJVs is irrelevant. But this just emphasises the point that the underlying model fails to capture virtually all of the factors that make RJVs interesting in the first place.

There is an immediate corollary.

Corollary 1

Suppose now that there are environmental externalities; that firms undertake environmental R&D which lowers emissions per unit of output; and that, in addition to the R&D subsidy the government can also operate an emissions tax. Suppose also that all the other assumptions of Result 1 hold. Then, once again, the cooperative and non-cooperative equilibria achieve exactly the same level of welfare.

Proof. The fact that the government has an emissions tax means that it can now control output, and so can now achieve the first-best. So choose output per firm and R&D per firm so as to achieve the first-best. Then, whether firms act cooperatively or non-cooperatively, choose the tax rate and R&D subsidy per firm so as to achieve the first-best.

This corollary allows us to get an immediate generalisation of the results in Katsoulacos and Xepapadeas (1996) from the case of the non-cooperative equilibrium that they analysed to that of a co-operative equilibrium.

This shows that in order to have an interesting theory of the interaction between environmental policies and RJV performance, one needs a more interesting model of R&D – one which gives scope for RJVs to achieve some of the objectives they are supposed to achieve. Recent papers by Katsoulacos and Ulph (1998a&b) have gone some way to correcting the weaknesses of the existing RJV literature, and so of providing a better account of how RJVs perform. Their models have the following features:

(i) Information-sharing is endogenous in both the cooperative and non-cooperative equilibria. In particular, the possibility of licensing is allowed in the non-cooperative equilibrium.

(ii) They allow for the possibility of both complementarity and substitutability between research discoveries.

(iii) They determine the number of research labs that will be active in the cooperative equilibrium[11].

For the case where there are just two firms they obtain the following results[12].

- Firms may not share information within an RJV. When RJVs withhold information they do so for anti-competitive reasons. For example, this will happen whenever industry profits are higher when one firm has lower costs than the other and can exploit this to exercise some degree of monopoly power. However the conditions under which information is shared in an RJV are exactly the same as those under which it is licensed in a non-cooperative equilibrium. Hence, in this two firm setting, RJVs perform no better nor worse than the non-cooperative equilibrium at the *information-sharing* stage of innovation decisions.
- RJVs may close a lab, but may do so for two reasons: to eliminate needless duplication, and to avoid competition that arises when both firms discover.

- While RJVs may give rise to a higher level of welfare than in the non-cooperative equilibrium, there is a range of circumstances under which they do not.

In this paper we wish to explore the interaction between environmental policy and the performance of environmental RJVs within the framework for analysing RJV performance proposed by Katsoulacos and Ulph. To understand some of the issues involved in undertaking this exercise we briefly set out the main features of a very simple version of the Ulph and Katsoulacos (1998) model adapted to the case of environmental innovation.

There are two firms producing a homogeneous product. Initially both firms use a technology whereby emissions per unit of output are $\bar{e} > 0$. Firms undertake R&D in order to discover a new technology for which emissions per unit of output are $\underline{e}, \quad 0 < \underline{e} < \bar{e}$. Each firm's probability of discovery depends solely on the R&D that it does, and these probabilities are independent. There are three possible outcomes of the R&D process: (i) neither firm discovers the new technology; (ii) both firms discover the new technology, but, since they have discovered the same thing, there is nothing to be gained from sharing the information[13]; (iii) one firm alone discovers, in which case a decision has to be made as to whether it reveals the new technology to the firm which has not discovered.

Assume for the moment that the only policy instruments open to the government are (a) an emissions tax and (b) the decision as to whether or not to allow firms to form RJVs. As in all the literature on RJVs we assume that if firms are allowed to co-operate on decisions relating to innovation, they are forced to compete in the output market.

In modelling the impact of the emissions tax on the performance of RJVs, an important issue arises as to when in the decision-making process this decision gets taken. Notice that, **leaving aside the tax-setting decision**, the decisions made by firms and the government constitute a six-stage game.

1: *RJV Policy* The government decides whether or not to allow RJVs.

2: *RJV Formation*	If RJVs are allowed, firms choose whether or not to form one.
3: *Research Design*	Firms choose the number of labs to operate.
4: R&D	Firms choose the amount of R&D to do in each lab.
5: *Information Sharing*	Conditioning on the outcome of the R&D decisions firms choose whether or not to share information.
6: *Output*	Firms choose output in a non-cooperative Cournot equilibrium

To understand the impact of the environmental policy instrument (emissions tax), notice that there are many different assumptions one can make about when this instrument gets chosen and the information available to the government when the decision gets taken. This timing issue reflects the ability of the government to commit itself to the decision. To illustrate this point, consider two possible assumptions that we could make.

Assumption 1 Government Unable to Commit

Here the government sets the tax rate at the start of stage 6, after it has learnt what technology each of the two firms is operating, but before firms have chosen output. The tax will be set so as to maximise welfare conditional on the technologies employed by the two firms. This set-up corresponds to the conventional static analysis of environmental policy with given technologies. Notice that effectively the government sets three tax rates: t^{11}, t^{10}, t^{00} depending respectively on whether each firm has the new technology, only one firm has the new technology, or neither firm has the new technology. The tax rate chosen by the government in each of these three states will involve balancing the two product-market failures discussed above. Thus the government wants high taxes to discourage emissions but low taxes to promote competition. Notice that since all the R&D and information-sharing decisions have already been taken, the taxes chosen at this stage will be exactly the same whether or not firms have co-operated. So the taxes are conditioned only on technology, not on the previously taken decision as to whether or not to co-operate. Let $\hat{t}^{11}, \hat{t}^{10}, \hat{t}^{00}$ be the optimum taxes set under this assumption.

Assumption 2 Government Has Some Ability to Commit

Here we could think of the tax being set at the start of stage 5 - after firms have chosen R&D and after the outcome of the R&D race is known, but before the information-sharing decision is taken. Notice that what the government announces are the taxes that it will set in Stage 6 conditional on the technologies that each firm will have at that stage - i.e. conditional on the information-sharing decision that is about to be made at stage 5. Now there are 3 possible situations the government can be in at the start of stage 5.

(i) Both firms have discovered the new technology. Here the only possible state that can arise at the start of Stage 6 is state 11, and since there is no information-sharing decision to be taken, it will simply announce $\hat{t}^{11}$.

(ii) Neither firm has discovered the new technology. By analogous reasoning the government will announce $\hat{t}^{00}$.

(iii) One firm has discovered the new technology and the other firm has not. Now the economy will be in either state 11 or state 10 at the start of Stage 6, but now the choice of tax rates in these two states can influence the information-sharing decision. Obviously the optimal thing for the government to do is to announce a tax $\tilde{t}^{10}$ that is so high that the firms will choose to fully share information.

Thus by being able to fully commit itself at the *information sharing* stage in the process, the government can induce the first-best level of information sharing in both the cooperative and non-cooperative equilibria.

We could think of taxes being set at yet earlier stages in the decision-making process, and, in general the taxes that are set will depend on the precise stage at which the decision is made. Rather than conduct an exhaustive analysis of all possible situations, we will confine attention to the case where the government is unable to commit, and explore the implications of this assumption for the desirability of permitting RJVs. We will contrast our conclusions with those obtained by Katsoulacos and Ulph (1998c) for the case of non-environmental R&D.

Before proceeding to the detailed model, notice the following two points.

Firstly, once we take account of the decision about environmental tax rates, we now effectively have the following seven-stage game.

1: *RJV Policy*	The government decides whether or not to allow RJVs.
2: *RJV Formation*	If RJVs are allowed, firms choose whether or not to form one.
3: *Research Design*	Firms choose the number of labs to operate.
4: *R&D*	Firms choose the amount of R&D to do in each lab.
5: *Information Sharing*	Conditioning on the outcome of the R&D decisions, firms choose whether or not to share information.
6: *Emissions Tax*	The government sets environmental taxes t^{11}, t^{10}, t^{00} conditioning on the technology that each firm has as a result of the outcomes of stages 4 and 5.
7: *Output*	Firms choose output in a non-cooperative Cournot equilibrium

Secondly, given the stage at which they are set, the environmental taxes chosen by the government will be exactly the same irrespective of whether or not firms have made their decisions at stages 3, 4 and 5 in a cooperative or non-cooperative fashion. It therefore follows that, if they are allowed to do so, firms will indeed choose to form an RJV at stage 2.

In the next section we want to explore what decision the government should take at stage 1. From the above discussion it follows that this just reduces to the question of whether expected social welfare is greater if the decisions made at stages 3, 4 and 5 are made cooperatively or non-cooperatively. It is important to appreciate that the **issues** arising in this comparison of the cooperative and non-cooperative equilibria are exactly the same as in Ulph and Katsoulacos (1998). The crucial point is that the decisions made at stages 6 and 7 are very different, and the question is therefore how these differences affect our assessment of the balance of factors at stages 3, 4 and 5. There are three key differences:

(a) The government has an instrument that can influence output decisions.

(b) The presence of environmental damage means that there are two wedges between the profits that firms use to guide their decisions, and the social welfare calculations that the government will use: consumer surplus, and environmental damage. This will influence the magnitude of the undervaluation effect.

(c) Since the tax rate will depend on decisions about information-sharing, the relationship between profits and surplus will vary across states in a complex way.

Taken together these three factors will affect whether the cooperative or non-cooperative equilibrium comes closer to achieving the socially optimal innovation decisions.

Section 2 The Model

Consider a closed economy in which there are just two goods - a “dirty” good whose production causes emissions of some pollutant, and “expenditure on all other goods”. Let X denote aggregate consumption/production of the dirty good and Z the aggregate expenditure on all other goods.

There is a single consumer with utility function

$$u(X,Z) \equiv aX - \frac{1}{2}.X^2 + Z$$

There are two firms producing X. Denote output of firm i by $x_i > 0, i = 1,2$, so $X = x_1 + x_2$. There is a perfectly competitive sector producing Z under constant returns to scale. Z is numeraire.

There are two possible technologies for producing X – an *old* (i.e. existing) technology and a *new* one that has yet to be discovered. For each technology, unit costs of production are c, $0 < c < a$. Emissions per unit of output with the new technology are $\underline{e} = 1$, and with the old technology $\bar{e} = 1 + q$, $0 < q < 1$. Thus technologies differ only in their environmental attributes – i.e. we are dealing with purely environmental innovation. The parameter θ provides a measure of how much better the new technology is compared to the old one in terms of its emissions properties.

If firm i produces output x_i using a technology that generates emissions per unit of output $e_i \in \{1, 1+q\}$, then the total emissions, E, produced by the two firms are $E = x_1.e_1 + x_2.e_2$. We assume that the damage done by these emissions is given by the function $D(E) = \frac{d}{2}.E^2$.

In order to discover the new technology with lower emission levels firms, undertake R&D. If the two firms act non-cooperatively they each operate their own independent lab. If they form an RJV then, at stage 3, they can choose to either continue to operate one lab each, or to operate a single combined lab.

In stage 4 firms choose the amount of R&D to do in each lab. The amount of R&D a lab does determines the probability that it will discover the new technology. If both firms undertake R&D then each has an independent probability of discovery which depends solely on the amount of R&D which it itself undertakes. Thus, as in Katsoulacos and Ulph (1998a), there are no R&D input spillovers, only R&D output spillovers.

As in Ulph and Katsoulacos (1998), we assume that the R&D expenditure that a lab needs to undertake in order to get a probability of discovery $p, \quad 0 \le p \le 1$, is

$$g(p) \equiv \frac{1}{1-\beta}\left\{1-(1-p)^{1-\beta}\right\} - p, \quad 0 < \beta < 1$$ [14].

Thus

(i) $g(0) = g'(0) = 0; \quad g''(0) = \beta > 0$;

(ii) $\forall p, \quad 0 < p < 1 \quad g(p) > 0; \quad g'(p) = (1-p)^{-\beta} - 1 > 0; \quad g''(p) = \beta(1-p)^{-\beta-1} > 0$;

(iii) As $p \to 1, \quad g(p) \to \frac{\beta}{1-\beta}, \quad g'(p) \to \infty$.

The parameter β reflects the extent of decreasing returns to R&D in each lab. As discussed in Ulph and Katsoulacos (1998) this is an important determinant of whether RJVs will choose to operate one or two labs.

In Stage 5 decisions are taken about sharing the information resulting from the discoveries made in Stage 4. There are three possible outcomes of Stage 4.

(a) Neither firm discovers the new technology. Since no information has been discovered, there is no information to be shared, and so both firms continue to operate with a technology in which emissions per unit of output are $\bar{e} = 1 + \theta$.

(b) Both firms discover the new technology. We assume that in this case, while each firm has obtained some information, it is exactly the same information, and so there is absolutely nothing to be gained by sharing it[15]. The reason for making this assumption is that, as we will see below, it introduces the possibility of needless duplication of research effort - one of the market failures that research joint ventures are supposed to alleviate. Thus in this case each firm now operates with a technology in which emissions per unit of output are $\underline{e} = 1$.

(c) <u>One firm alone discovers the new technology</u>. The firm that has discovered the new technology will now have emissions per unit of output of $\underline{e} = 1$. Now there is some information to be shared, and something to be gained (at least by the recipient) from sharing it. We assume that there are just two possible decisions to be made about information sharing[16].

    (i) No information is shared. In this case the emissions per unit of output of the firm that has not discovered will be $\bar{e} = 1 + q$[17].

    (ii) Full information-sharing takes place. In this case the emissions per unit of output of the firm that has not discovered will be $\underline{e} = 1$[18].

Notice now that if one firm alone discovers the new technology, and if it fully shares the information with the other firm, then the outcome will be precisely the same as if both firms had discovered - each firm will have emissions $\underline{e} = 1$. Thus there is nothing to be gained by having both firms discover the new technology that could not be gained by having just one firm discover the new technology and sharing the results. In this sense there has clearly been a duplication of research effort.

In Stage 6 the government sets the environmental tax rate. Now there are three possible situations that can occur at the start of Stage 6, depending on which technology each firm has.

(a) <u>Neither firm has the new technology</u> This situation can arise only if nether firm discovers the new technology. Variables relating to this situation will be described by a superscript 00.

(b) <u>Both firms have the new technology</u> This situation can arise if either both firms discover the new technology, or if only one does and information is fully shared. Variables relating to this situation will be described by the superscript 11.

(c) Only one firm has the new technology This situation can arise only if just one firm discovers the new situation and information is not shared. Aggregate variables relating to this situation will be described by the superscript 10. Variables relating to individual firms will carry the superscript 10 for the firm which has the new technology and 01 for the firm that does not.

Thus the government effectively sets three tax rates: t^{11}, t^{10}, t^{00}.

Finally in Stage 7 output decisions are taken conditional on the marginal costs that each firm will have as a result of the decisions taken in the previous three stages. We assume that collusion over output is forbidden. Consequently the output of the two firms is determined as a non-cooperative equilibrium. In this paper we confine attention to the non-cooperative Cournot equilibrium. However the nature of this equilibrium depends on the taxes set by the government in Stage 6.

Section 3 The Solution and The Welfare Measures

As is conventional we solve the model backwards.

Stage 7 The Cournot Equilibrium

If firm i has technology $e_i \in \{1, 1+\boldsymbol{q}\}$, and if the government has imposed an emissions tax *t* per unit of emissions, then, in an interior Cournot equilibrium, the output of firm *i* is

$$x_i = \frac{(a-c)+t\left(e_j - 2e_i\right)}{3}, \quad i = 1,2;\ j \neq i, \qquad (1)$$

and the profits it makes are

$$\boldsymbol{p}_i = \left(x_i\right)^2.$$

Stage 6. The Tax-Setting Decision

Since all the innovation decisions have already been taken, all the government can influence at this stage is the output equilibrium in Stage 7. All that matters to the government then is the flow of welfare comprising consumer surplus, producer surplus (profits) and environmental damage.

If firm *i* produces output x_i using a technology that generates emissions per unit of output $e_i \in \{1, 1+\boldsymbol{q}\}$, then the total emissions, *E*, produced by the two firms are $E = x_1.e_1 + x_2.e_2$. As noted above, we assume that the damage done by these emissions is given by the function $D(E) = \frac{d}{2}.E^2$. The flow of social welfare in this output market situation is therefore

$$W\left(x_1, x_2; e_1, e_2\right) \equiv (a-c)\left(x_1+x_2\right)-\frac{1}{2}\left(x_1+x_2\right)^2-\frac{d}{2}\left(x_1.e_1+x_2.e_2\right)^2 \qquad (2)$$

By substituting the equilibrium outputs in (1) into the social welfare function (2), we can determine social welfare as a function of the tax rate alone. Consequently we can determine the optimum tax rate and the equilibrium to which it gives rise.

To understand this more fully, it is useful to consider in turn two separate cases.

Case 1 Both firms have the same emissions per unit of output $e \in \{1, 1+q\}$.

Notice that in this case both firms will choose identical output, and so it follows from (1) that welfare depends solely on the aggregate level of output, *X*. Thus we can write

$$W=(a-c)X-\frac{1+d.e^2}{2}.X^2 . \qquad (3)$$

From (2) we know that equilibrium aggregate output is

$$X=\frac{2}{3}.\left(a-c-t.e\right), \qquad (4)$$

so it now follows that, by suitable choice of *t*, the government can achieve the first-best level of welfare.

From (3) it follows that the first-best level of aggregate output is

$$\hat{X}=\frac{a-c}{1+d.e^2}.$$

Combining (3) and (4) we see that the tax rate that achieves the optimum is

$$\hat{t}=\frac{(a-c).\left(2d.e^2-1\right)}{2.e.\left(1+d.e^2\right)}$$

It is straightforward to check that:

(i) welfare in the social optimum is

$$\hat{W}(e) = \frac{1}{2}.\frac{(a-c)^2}{1+d.e^2} \,;$$

(ii) industry profits in the social optimum are

$$\Sigma(e) = \frac{1}{2}.\left(\frac{a-c}{1+d.e^2}\right)^2$$

Thus

$$\Sigma(e) = \frac{\hat{W}(e)}{1+d.e^2}$$

This shows that industry profits understate social welfare, and that the gap is larger when both firms have the old technology than when they both have the new technology.

To ease notation later on, let $t^{11}, W^{11}, \Sigma^{11}$ ($t^{00}, W^{00}, \Sigma^{00}$) denote the optimal tax rate and the flow levels of welfare and industry profits when both firms have the new (resp. old) technology. We have

$$t^{11} = \frac{(a-c).(2d-1)}{2(1+d)}; \quad W^{11} = \frac{(a-c)^2}{2(1+d)}; \quad \Sigma^{11} = \frac{1}{2}.\left(\frac{a-c}{1+d}\right)^2$$

$$t^{00} = \frac{(a-c).\left[2d.(1+q)^2-1\right]}{2.(1+q).\left[1+d.(1+q)^2\right]}; \quad W^{00} = \frac{(a-c)^2}{2.\left[1+d.(1+q)^2\right]}; \quad \Sigma^{00} = \frac{1}{2}.\left(\frac{a-c}{1+d.(1+q)^2}\right)^2$$

Case 2 Firm 1 has the old technology and firm 2 the new technology.

This case can only arise if one firm has discovered the new technology, but does not share the information.

Notice first of all that in general the government can now no longer obtain the first-best output equilibrium. Since the two firms have different technologies, they will choose different output levels. The first-best would require getting **both** of these output levels right, and, with just a single instrument – the environmental tax rate- this typically impossible to achieve. In particular the first best would require that only firm 2 be active, and so act as a monopolist. For this possibility to arise it would have to be the case that when the government sets the tax that would be optimal IF firm 2 were a monopolist, then firm 1's costs would be so high that it would not be willing to enter. It is straightforward to confirm that this can only arise if $\boldsymbol{q} \geq \frac{d}{d-1} > 1$. Since, in this paper, we assume that $\boldsymbol{q} \leq 1$ we can rule this possibility out.

Indeed, throughout the paper we wish to confine attention to the case where, in the optimum, both firms are active. To analyse this situation, we will begin by **assuming** that both firms are active, derive the optimum tax rate under this assumption, and then check that, given this tax rate, both firms are indeed active.

In an interior Cournot equilibrium, the individual and aggregate outputs of the two firms are as follows.

$$x_1 = \frac{a - c - t(1 + 2\boldsymbol{q})}{3}$$

$$x_2 = \frac{a - c - t(1 - \boldsymbol{q})}{3}$$

and $$X = \frac{2(a-c) - t(2+\theta)}{3}.$$

Total emissions are

$$E = X + \theta . x_1 = \frac{(a-c).(2+\theta) - 2t.(1+\theta+\theta^2)}{3}.$$

Social welfare is $W = (a-c).X - \frac{1}{2}.X^2 - \frac{d}{2}.E^2$, and so the optimal tax arises where

$$W' = [(a-c) - X].X' - d.E.E' = 0.$$

Carrying out the calculation we find that

$$t^{10}(\theta, d) = \frac{(a-c).(2+\theta).[2d(1+\theta+\theta^2)-1]}{d.[2(1+\theta+\theta^2)]^2 + (2+\theta)^2} \qquad (5)$$

Before discussing the properties of the optimum tax, we need to confirm that this tax rate is consistent with our assumption of an interior Cournot equilibrium – i.e. with a positive output for firm 1. It is easy to see that this latter condition requires that

$$t^{10}(\theta, d) < \frac{(a-c)}{1+2.\theta}.$$

We note below that t^{10} is a strictly increasing function of *d*, so the above condition requires that

$$d < \bar{d}(\theta) \equiv \frac{2+3\theta+\theta^2}{2.\theta.(1+\theta+\theta^2)}.$$

It is straightforward to check that $\bar{d}(\theta)$ is strictly decreasing in θ.

For later purposes, Table 1 shows the values taken by this function for a range of values of $0 < q \leq 1$.

Table 1

θ	$\bar{d}(q)$
0.1	10.405
0.3	3.585
0.5	2.142
0.7	1.497
1	1

We can also invert $\bar{d}(q)$ to obtain the function $\bar{q}(d)$ which gives, for any d an upper bound on θ for which the optimal tax yields an interior Cournot equilibrium.

Properties of the optimal tax when firms do not share information:

As noted above, it is easy to check that t^{10} is a strictly increasing function of d. Thus, as we would expect, the more damaging are emissions, the higher is the optimal tax.

The crucial question is how t^{10} varies with θ. For, later on, we will want to know whether the tax rate is higher if firms do not share information than if they do share information. That is we will want to know whether $t^{10}(q,d) \overset{>}{\underset{<}{-}} t^{11}$. Now it follows by definition and from the formula in (5) that

$$t^{10}(0,d) = \frac{(a-c)(2d-1)}{2(d+1)} = t^{11},$$

so what we really want to know is whether $t^{10}(q,d) \overset{>}{\underset{<}{-}} t^{10}(0,d)$.

To answer this question consider first two extreme cases.

1. When $d = 0$,

$$t^{10}(\theta,0) = -\frac{a-c}{2+\theta} < 0; \quad \frac{\partial t^{10}}{\partial \theta} = \frac{a-c}{(2+\theta)^2} > 0 .$$

Thus, as we would expect, when there is no environmental damage the government imposes a subsidy to correct the loss arising from imperfect competition. However, because the subsidy is imposed on emissions rather than on output, the subsidy itself induces what is in this case an unwarranted asymmetry between the two firms. A larger value of θ means the subsidy has to be smaller (i.e. the negative tax larger) in order to reduce the unwarranted distortion.

2. When $d \to \infty$,

$$t^{10}(\theta,\infty) = \frac{(a-c).(2+\theta)}{2(1+\theta+\theta^2)} > 0; \quad \frac{\partial t^{10}}{\partial \theta} = -\frac{(a-c).(1+4\theta+\theta^2)}{2(1+\theta+\theta^2)^2} < 0$$

Accordingly for the five values of *d* shown in the right-hand column of Table 1 above, we have calculated the value of t^{10} as θ ranges over values in the interval $0 \le \theta \le \bar{\theta}(d)$. The results are presented in Tables A1-A5 in the Appendix.

These show that when *d* is small the optimal tax first rises and then falls with θ, while when *d* is large then the optimal tax is a strictly decreasing function of θ.

The intuition behind these results is as follows. In setting the tax the government is trying to correct two distortions: (a) that caused by imperfect competition, and (b) that caused by pollution. Consider these in turn.

(a) The larger is θ the lower is aggregate output and so the greater the loss arising from imperfect competition. This suggests that the optimal tax should fall with θ.

(b) When *d* is small, so too is the optimal tax, and, when $\theta \approx 0$, an increase in θ causes aggregate emissions to rise – which calls for an increase in the optimal tax to correct this distortion. On balance the second factor outweighs the first when $\theta \approx 0$ causing the optimal tax to rise with θ. However, when *d* is large, so too is the optimal tax, and it is easy to check that in this case aggregate emissions are a strictly decreasing function of θ, so this second factor also calls for the optimal tax to fall with θ.

Having determined the optimal tax, we can substitute this back into the expressions for output, profits and welfare, and so determine aggregate profits, Σ^{10}, and aggregate welfare, W^{10} as functions of the underlying parameters *d* and θ.

These profit and welfare expressions can then be used to determine the equilibrium and optimum information-sharing and R&D decisions in stages 2 and 1 respectively. To these we now turn.

Stage 5 The Information-Sharing Decision.

Suppose that just one firm has discovered the new technology. If it does not share information then the resulting levels of aggregate welfare and aggregate profits will be W^{10} and Σ^{10} respectively. If information is shared then the resulting levels of aggregate welfare and aggregate profits will be W^{11} and Σ^{11} respectively.

As discussed in Ulph and Katsoulacos (1998), information-sharing will be socially desirable iff $W^{11} > W^{10}$, and will be privately profitable *in both the cooperative and non-cooperative equilibria* ***(under licensing)*** iff $\Sigma^{11} > \Sigma^{10}$.

Unfortunately, the expressions for aggregate profits, Σ^{10}, and aggregate welfare, W^{10} that emerge from the analysis in Stage 6 are sufficiently complex that it is extremely difficult to explore these inequalities analytically, so we have had to explore them numerically. Tables A1 to A5 in the appendix give the computed values for profits and welfare as θ ranges over values in the interval $0 \le q \le \bar{q}(d)$. In reading these tables it is important to bear in mind that the first row, corresponding to the case $q = 0$ corresponds to the situation where both firms have a technology with emission levels of 1, and so the levels of welfare and profits here are W^{11} and Σ^{11} respectively.

An inspection of the Tables shows that in all cases welfare is lower when $\theta > 0$ than when $\theta = 0$, i.e. that $W^{11} > W^{10}$, and so, as we would expect, full information is socially desirable. This is because, when information is fully shared, both firms have the least polluting technology, and the government can then use its tax powers to achieve the first-best levels of output.

Let us now consider the private information-sharing decision of the two firms. From Ulph and Katsoulacos (1998) we know that firms will choose not to share information whenever the firm with the new technology has a sufficient cost advantage. This enables it to exercise significant market power, and so the resulting industry profits are higher than would be the case if both firms had the new low-cost technology, and the industry was consequently very competitive. The difference now is that the cost difference between firms depends on both the difference in technology, as reflected in the parameter θ, and on the tax rates t^{11}, t^{10}.

To understand what is going on here, consider first the case where the government sets some arbitrary tax rate *t*, say, which is independent of the technologies actually used by the two firms, and thus is the same *whether or not information is shared*. Then it follows from the result in Ulph and Katsoulacos (1998) that information will definitely be shared if

$$t(2 + 5\theta) < a - c, \tag{6}$$

and will definitely not be shared if the inequality in (6) is reversed. This shows that the information-sharing condition depends on both the tax rate, *t*, and on the technology gap parameter, θ, and that information is shared when both *t* and θ are small.

As a variant on the above thought experiment, suppose now that instead of setting and arbitrary tax rate, the government sets the same tax rate t^{11} *whether or not information is shared*. Then (6) becomes,

$$q < \tilde{q}(d) \equiv \frac{6}{5(2d-1)} \qquad (7)$$

In the Appendix we present the values of $\tilde{q}(d)$ corresponding to each of the values of *d* in Table 1. We see that when *d* = 1, then $\tilde{q}(1) > \bar{q}(1)$, and so, if the government sets the tax rate t^{11} whether or not the information is shared, then, for this value of *d* information will always be shared – i.e. will be shared for all values of $q \in \left[0, \bar{q}(1)\right]$. However when *d* >1 then $\tilde{q}(d) < \bar{q}(d)$, and so information will not always be shared, i.e. will not be shared for all values of $q \in \left[0, \bar{q}(d)\right]$. In particular information will only be shared if emissions under the old technology are sufficiently close to those with the new technology.

An alternative way of seeing what is going on here is to let $\tilde{l}(d) \equiv MIN\left[\frac{\tilde{q}(d)}{\bar{q}(d)}, 1\right]$ measure the fraction of the range of feasible values of θ over which information is shared. Then we see from the Appendix that $\tilde{l}(1) = 1$, but that $\tilde{l}(d)$ is a strictly decreasing function of *d*. In this sense we conclude that information-sharing becomes less likely the larger the value of *d*.

These results are in line with the work of Ulph and Katsoulacos (1998). Information-sharing is likely when the cost differences are small. When the damage is small then so too is the optimal tax rate, and so cost differences are small for all $q \in \left[0, \bar{q}(d)\right]$. However when damage is large, so too is the tax rate, and so information will only be shared when the underlying technology gap parameter θ is sufficiently small.

Finally, when we recognise that the government will in fact set a different tax rate t^{10} if information is not shared from the tax rate t^{11} that will be set if information is shared, then we need to know whether or not $\Sigma^{11} > \Sigma^{10}$. From the discussion above we know that Σ^{11} is the value of industry profits when $q = 0$. So, in looking at the tables in the Appendix, we can determine whether or not information is shared in any given situation, by simply comparing the value of industry profits, Σ^{10} with that given in the first row of the Table.

We see that when d = 1 then, for all positive values of $\theta \le \bar{\theta}(1)$, industry profits are lower than in the case where $\theta = 0$ - i.e. information is always shared.

However, when d > 1, then, by interpolation, there exists a $\breve{\theta}(d), 0 < \breve{\theta}(d) < \bar{\theta}(d)$ such that industry profits are the same when $\theta = \breve{\theta}(d)$ as when $\theta = 0$. This implies that information will be shared when $0 < \theta < \breve{\theta}(d)$ and will NOT be shared when $\breve{\theta}(d) < \theta \le \bar{\theta}(d)$.

By analogy with what we did above, we can let $\breve{\lambda}(d) \equiv MIN\left[\frac{\breve{\theta}(d)}{\bar{\theta}(d)},1\right]$ denote the fraction of the range of feasible values of θ over which information is shared when the government sets different tax rates t^{11}, t^{10}. From the Appendix we see that when d is small then $\breve{\lambda}(d) > \tilde{\lambda}(d)$, but that when d is large then $\breve{\lambda}(d) < \tilde{\lambda}(d)$. Thus when the government sets different taxes if firms share information than if they do not, then, compared to the situation where the same tax rate is set irrespective of the information-sharing decision, information-sharing becomes more likely when damage is small, but less likely when the damage is large. This latter result follows from the result noted above. When damage is small taxes tend to increase with θ, which, *ceteris paribus* lowers profits when information is not shared and so makes information-sharing more attractive than in the case where taxes do not change with θ. However, when damage is large taxes tend to fall with θ, which, *ceteris paribus* raises profits when information is not shared and so makes information-sharing less attractive than in the case where taxes do not change with θ.

Having understood the information-sharing decision we can turn finally to the R&D decisions.

Stages 3&4 The R&D Decisions

We have to determine the amount of R&D done by each of the two labs in each of the two equilibria – cooperative and non-cooperative. In particular, in considering the cooperative (RJV) equilibrium we have to allow for the possibility of an asymmetric solution in which one of the labs does no R&D.

Before turning to the more detailed analysis, it is important to make three general points about the nature of the R&D decisions.

1. As noted in Katsoulacos and Ulph (1998a) and in Ulph and Katsoulacos (1998), although, *ex ante*, the two firms are identical, the R&D outcomes need not be. In particular, in both the social optimum and in the cooperative equilibrium, it may turn out to be optimal to have only one firm undertake R&D. Whether or not this is the case turns on a trade-off between diminishing returns and needless duplication. The greater the extent of diminishing returns – the larger the parameter β in the R&D cost function – the more likely it is that both labs will be kept open.

2. In the non-cooperative equilibrium both firms will undertake R&D (and the equilibrium will be symmetric). This means that the non-cooperative equilibrium may be prone to a welfare loss of needless duplication,

3. When firms share information in the non-cooperative equilibrium, they do so through licensing. We assume that the license fee is determined by negotiation, and that the licensor and the licensee have equal bargaining power. So the license fee is just half way between the maximum price the licensee is willing to pay and the minimum price at which the licensor is willing to sell.

The detailed analysis of the R&D decisions is now very similar to that given in Ulph and Katsoulacos (1998), so in what follows we just briefly summarise the main points of their analysis.

The first of the above points makes it difficult to undertake any general analysis of the R&D decisions in the social optimum and in each of the two equilibria. Most of the analytical conclusions are therefore obtained in the easier case where both firms undertake R&D. As noted in our earlier papers, there are then two incentives driving the R&D decisions – *competitive threat*[19] and *profit incentive*[20].

Whether or no information is shared, the *profit incentive* is weakest in the cooperative equilibrium and strongest in the social optimum, with the *profit incentive* in the non-cooperative equilibrium lying between the other two. The *profit incentive* is strongest in the social optimum because welfare is greater than profits – essentially because of the wedge caused by environmental damage. The *profit incentive* is greater in the non-cooperative equilibrium than in the cooperative equilibrium, because most of the gains from having a firm innovate go to the firm that innovates.

When information is shared the *competitive threat* is zero in both the social optimum and in the cooperative equilibrium, since the aggregate outcome is exactly the same whether one firm or both discover. However the *competitive threat* is positive for the non-cooperative equilibrium since an individual firm will always lose if it fails to discover when the other firm has done so. The only difference that arises when information is not shared is that the *competitive threat* in the cooperative equilibrium is then negative, since, by definition, industry profits are lower when both firms discover than when only one does so.

The general conclusion then is that, when both firms undertake R&D, then:

(i) compared to the social optimum, the cooperative equilibrium always under-invests;

(ii) R&D spending will be higher in the non-cooperative equilibrium than in the cooperative equilibrium;

(iii) R&D spending in the non-cooperative equilibrium may be higher or lower than in the social optimum.

It is therefore far from obvious that RJVs necessarily perform better than the non-cooperative equilibria in terms of getting the levels of R&D spending right. Where they may potentially prove beneficial is in eliminating the needless duplication of R&D effort.

Stage 2 RJV Membership

As noted above this is trivial. Since the tax rates set in stage 6 do not depend on the RJV membership decision, and since, in a given environment firms are always better off co-operating than not co-operating, the firms will always join an RJV if RJVs are allowed.

Stage 1 RJV Policy

The government now has to decide whether or not to allow firms to form an RJV. We know that the information-sharing decision in Stage 5 will be exactly the same whether firms act co-operatively or non-cooperatively. So let

$$\tilde{W}^{10} \equiv \begin{cases} W^{11} & \text{if } \Sigma^{11} > \Sigma^{10} \\ W^{10} & \text{if } \Sigma^{10} > \Sigma^{11} \end{cases}$$

denote the level of welfare that will be achieved if, in Stage 4, one lab discovers the new technology and the other does not - allowing for the information sharing decision that will subsequently be made in Stage 5.

Let $p_i^n, \quad i = 1,2$ denote the non-cooperative equilibrium probabilities of discovery by each of the two labs as determined in Stages 3 and 4 of the game, and $p_i^c, \quad i = 1,2$ denote the corresponding probabilities in the cooperative (RJV) equilibrium.

Let $\overline{W}^n$ (resp. $\overline{W}^c$) denote the expected level of social welfare in the non-cooperative (resp. cooperative) equilibrium. Then the formula

$$\overline{W}^t = p_1^t.p_2^t.W^{11} + p_1^t.(1 - p_2^t).\tilde{W}^{10} + p_2^t.(1 - p_1^t).\tilde{W}^{10} + (1 - p_1^t).(1 - p_2^t).W^{00} - g(p_1^t) - g(p_2^t)$$

gives the expected level of social welfare in the equilibrium of type *t*.

To complete our analysis of the model, we have undertaken a numerical comparison of both the cooperative and non-cooperative equilibria and their associated levels of expected welfare. What we have done is as follows. We have set $a – c = 4$[21], and have chosen values for the parameter β and for a parameter l, $0 < l < 1$, which determines the magnitude of the parameter θ in relation to its upper bound $\bar{q}(d)$. Initially we have chosen values $b = 0.2$ and $l = 0.5$. For each of the values of d given in Table 1 above, and for the value of $q = l\bar{q}(d)$ we have solved for the following.

(i) The probability of discovery per firm in the social optimum – which we denote by $\hat{p}_i$, $i = 1,2$. In doing this calculation we take account of the fact that in the social optimum there would be full information-sharing;

(ii) The equilibrium levels of R&D spending in both the cooperative and non-cooperative equilibria – which we denote by p_i^C, p_i^N, $i = 1,2$ respectively. In doing these calculations we take account of the fact that information will be shared if $l \le \breve{l}(d)$, and will not be shared otherwise.

We use the convention that if one of the firms does not undertake R&D it is always the second. We have then computed the expected levels of welfare in the social optimum and in both the cooperative and non-cooperative equilibria. By definition expected welfare in each of the two equilibria is less than the expected welfare in the social optimum. We can therefore calculate the percentage welfare loss in each of the two equilibria. These are denoted by L^C, L^N for the cooperative and non-cooperative equilibrium respectively. For the case where $l \le \breve{l}(d)$, and so information is fully shared in both the cooperative and non-cooperative equilibrium, firms are making the socially optimal information-sharing decision, and so this welfare loss arises solely because firms are making the wrong R&D decisions. However, when $l > \breve{l}(d)$ firms are in addition making the wrong information-sharing decision. We then calculate the hypothetical level of welfare that would have arisen for the given equilibrium levels of R&D spending but assuming now that information is fully shared. Using this it is possible to decompose the overall welfare losses into welfare losses L_R^C, L_R^N that arise in each of the two equilibria because of the wrong R&D decisions, and welfare losses L_I^C, L_I^N that arise because the wrong information-sharing decision has been made.

Table 2 below presents the calculations for three values of d = 1; 2.142; 3.585 - no extra insights are obtained by including the calculations for the other two values of d It should be borne in mind that the associated values of $\breve{l}$ are 1; 0.704; and 0.443 respectively. So, with $l = 0.5$, information will be shared for the first two values of d but not for the third.

Table 2

d	1	2.142	3.585
$\hat{p}_1$	0.99	0.659	0.532
$\hat{p}_2$	0	0.659	0.532
p_1^C	0.982	0.551	0.354
p_2^C	0	0.551	0.354
L^C	0.03	0.67	4.47
L_R^C	0.03	0.67	1.55
L_I^C	0	0	2.91
$p_1^N = p_2^N$	0.899	0.762	0.57
L^N	1.98	0.69	3.2
L_R^N	1.98	0.69	0.07
L_I^N	0	0	3.12

A number of points emerge from this table.

1. When damage is low, so too are taxes. The returns to R&D in terms of either welfare or profits are high, and this causes firms to undertake a lot of R&D with a high probability of discovery. But this also means that the probability of duplication is also high. For this reason, in both the social optimum and the cooperative equilibrium, it pays to shut a lab. However, in the non-

cooperative equilibrium both labs operate, giving rise to significant losses from excessive duplication. Since, when damage is low, information is always shared, the only welfare losses arise from getting R&D decisions wrong, and the cooperative equilibrium performs significantly better than the non-cooperative equilibrium.

2. When damage is somewhat higher, so too are taxes, and the returns to R&D in terms of both welfare and profits are lower. The risk of duplication is now lower, and it turns out that in both the social optimum and the cooperative equilibrium, both labs are kept open. Compared to the social optimum the cooperative equilibrium under-invests in R&D and the non-cooperative equilibrium over-invests. The losses are of almost equal magnitude. Once again information is fully shared, so the R&D losses are the only ones that matter.
3. When damage is higher still, so too are taxes and the returns to R&D fall further, so further reducing the risk of needless duplication. Both labs are therefore always used. The non-cooperative equilibrium over-invests and the cooperative equilibrium under-invests, but now the loss from under-investment is considerably greater than the loss from over-investment, and, in terms of R&D decision-making the non-cooperative equilibrium now scores better than the cooperative equilibrium. However, with this level of damage, taxes fall with θ, which, *ceteris paribus*, raises the profits from not sharing information. Thus in this case information will not be shared, but, since the probability that just one firm will discover is higher in the non-cooperative equilibrium than in the cooperative equilibrium, the welfare loss from getting the information-sharing decision wrong is higher in the non-cooperative equilibrium than in the cooperative equilibrium. Nevertheless the difference is rather small, and is dominated by the better performance of the non-cooperative equilibrium in terms of R&D decision-making.
4. Thus the overall conclusion from this table is that RJVs outperform non-cooperative equilibria when damage is low, but the conclusion is reversed when the damage is high.

Tables A6 – A8 in the Appendix report the results of similar exercises for different parameter values. Thus in Table A6 we report the outcomes when there is more rapid diminishing to returns to R&D and $\beta = 0.5$. Now both labs are always kept open. Nevertheless the conclusions of Table 2 are broadly confirmed – RJVs do better when damage is small because over-investment in the non-cooperative equilibrium dominates the under-investment of the cooperative equilibrium. However the positions are reversed as damage increases.

Table A7 reports the outcomes when $\beta = 0.2$, but now λ is raised to 0.75. Now information is not shared when damage takes its intermediate value, and in this case the information-sharing loss from the RJV exceeds that in the non-cooperative equilibrium. Other than that, the results broadly confirm the findings of Table 2.

Finally Table A8 reports the outcomes when $\beta = 0.2$, but now $\lambda = 0.25$. Now information is always shared and both labs are always kept open. The performance of the RJV gets steadily worse as damage increases and so too does the extent of under-investment, whereas the performance of the non-cooperative equilibrium steadily improves as the extent of over-investment is reduced.

Conclusions

We have examined the performance of environmental RJVs, using a model in which (a) information-sharing is endogenous, (b) firms can choose to license their technology; (c) the number of labs that are operated is endogenous. Welfare losses can arise through (i) the failure to make the right-information-sharing decisions; (ii) the failure to operate the right number of labs – and so have excessive duplication of effort; (iii) getting the R&D decisions wrong through under- or over-investment. We have shown that an analysis of this issue requires a careful discussion of the informational and commitment powers of the government in setting its environmental policy.

In the context of a very simple model in which there is very limited commitment, we have shown the following.

(i) As in Ulph and Katsoulacos (1998)RJVs will share information under precisely the same circumstances as in the non-cooperative equilibrium.

(ii) Information-sharing is more likely when damage, and hence taxes are low.

(iii) When damage is low RJVs perform better in R&D decision-making than does the non-cooperative equilibrium, and this for two reasons. Since the returns to R&D are high they are more likely to avoid the risk of needless duplication. The loss from under-investment by the RJV is smaller than the loss from over-investment in the non-cooperative equilibrium.

(iv) As damage rises the under-investment by the RJV increases and the over-investment in the non-cooperative equilibrium falls.

A tentative conclusion is that RJVs do better than non-cooperative arrangements when environmental damage is low, but worse when environmental damage is high.

Journal of Industrial Economics ,46, 333-357.

Katsoulacos, Y. and D. Ulph (1998b) "Innovation Spillovers and Technology *Annales d'Economies et Statistiques*, 49/50, 589-607.

Katsoulacos, Y. and Xepapadeas, A. (1996), "Environmental innovation, spillovers and optimal policy rules", in C. Carraro, Y. Katsoulacos and A. Xepapadeas (eds.), *Environmental Policy and Market Structure*, Kluwer, Dordrecht, pp 143-150.

Petrakis, E and J. Poyago-Theotoky (1997), "Environmental Impact of Technology Policy: R&D Subsidies versus R&D Cooperation", *University of Nottingham Discussion Paper*, 97/16.

Poyago-Theotoky, J. (1997), (ed.) *Competition, Cooperation, Research and Development*, Macmillan.

Scott, J.T. (1996), "Environmental Research Joint Ventures among Manufacturers", *Review of Industrial Organisation*, **11**, pp 655-679.

Ulph, A. (1993), “Environmental Policy and International Trade When Governments and Producers Act Strategically”. *Journal of Environmental Economics and Management*.

Ulph, A. (1996), “Strategic Environmental Policy”, in C. Carraro, Y. Katsoulacos and A. Xepapadeas (eds.), *Environmental Policy and Market Structure*, Kluwer, Dordrecht, pp 99 -127.

Ulph, A. and D. Ulph (1996), “Trade, strategic innovation and strategic environmental policy - a general analysis”, in C. Carraro, Y. Katsoulacos and Xepapadeas (eds.), *Environmental Policy and Market Structure*, Kluwer, Dordrecht, pp 181-208.

Ulph, D. (1994), “Strategic Innovation and Strategic Environmental Policy” in C. Carraro (ed.) *Trade Innovation, Environment*, Kluwer, Dordrecht.

Ulph, D. (1997) “Environmental Policy and Technological Innovation”, in C. Carraro and D. Siniscalco (eds.) *New Directions in the Economic Theory of the Environment*, Cambridge University Press: Cambridge, pp 43-68.

Ulph, D. and Y. Katsoulacos (1998) “Endogenous Spillovers and the Welfare Performance of Research Joint Ventures”, *mimeo*.

</ref_section>

Appendix

Table A1 $d = 1,\quad \bar{q} = 1,\quad \tilde{q} = 1.2,\quad \tilde{l} = 1$

θ	t^{10}	Σ^{10}	W^{10}
0	25	1250	2500
0.1	27.4	1130.1	2384.9
0.2	29.6	1027.4	2291.5
0.3	31.4	950.0	2220.8
0.4	32.8	902.2	2172.7
0.5	33.8	884.3	2145.3
0.6	34.3	893.8	2136.1
0.7	34.5	926.3	2142.1
0.8	34.3	976.7	2160.3
0.9	34.0	1039.8	2187.9
1	33.3	1111.1	2222.2

Information Shared: $\forall q,\quad 0 \le q \le \bar{q} \Rightarrow \breve{l} = 1$

Table A2 $d = 1.497,\quad \bar{q} = 0.7,\quad \tilde{q} = 0.6,\quad \tilde{l} = 0.86$

θ	t^{10}	Σ^{10}	W^{10}
0	39.9	801.9	2002.4
0.07	41.0	740.9	1926.4
0.14	41.9	694.1	1866.4
0.21	42.6	663.3	1822.3
0.28	43.0	649.1	1793.1
0.35	43.3	651.4	1777.8
0.42	43.3	668.8	1774.9
0.49	43.1	699.5	1782.7
0.56	42.8	741.6	1999.7
0.63	42.3	792.7	1824.1
0.7	41.7	850.7	1854.6

By Interpolation, $\breve{q} = 0.641 \Rightarrow \breve{l} = 0.916$

Table A3 $d = 2.142,\quad \bar{q} = 0.5,\quad \tilde{q} = 0.365,\quad \tilde{l} = 0.73$

θ	t^{10}	Σ^{10}	W^{10}
0	52.3	506.5	1591.3
0.05	52.5	476.9	1542.7
0.1	52.7	457.4	1505.0
0.15	52.7	448.1	1477.8
0.2	52.6	448.8	1460.4
0.25	52.5	459.0	1452.2
0.3	52.2	478.1	1452.2
0.35	51.8	505.3	1459.7
0.4	51.3	539.5	1473.8
0.45	50.7	579.7	1493.5
0.5	50.0	625.1	1518.1

By Interpolation, $\breve{q} = 0.352 \Rightarrow \breve{l} = 0.704$

Table A4 $d = 3.585,\quad \bar{q} = 0.3,\quad \tilde{q} = 0.194,\quad \tilde{l} = 0.65$

θ	t^{10}	Σ^{10}	W^{10}
0	67.3	237.8	1090.5
0.03	67.0	229.3	1067.7
0.06	67.0	225.8	1050.2
0.09	66.3	227.2	1037.7
0.12	65.9	233.2	1030.1
0.15	65.4	243.6	1027.1
0.18	64.9	258.2	1028.2
0.21	64.4	276.6	1033.3
0.24	63.8	298.5	1042.0
0.27	63.2	323.6	1054.0
0.3	62.5	351.6	1069.0

By Interpolation, $\breve{q} = 0.133 \Rightarrow \breve{l} = 0.443$

Table A5 $d = 10.405, \quad \bar{q} = 0.1, \quad \tilde{q} = 0.06, \quad \tilde{l} = 0.6$

θ	t^{10}	Σ^{10}	W^{10}
0	86.8	38.4	438.4
0.01	86.5	38.1	434.8
0.02	86.2	38.7	432.1
0.03	85.9	40.0	430.1
0.04	85.5	42.1	429.0
0.05	85.2	44.9	428.6
0.06	84.8	48.4	428.9
0.07	84.5	52.7	430.0
0.08	84.1	57.6	431.8
0.09	83.7	63.2	434.2
0.1	83.3	69.4	437.3

By Interpolation, $\breve{q} = 0.015 \Rightarrow \breve{l} = 0.15$

Table A6 $\boldsymbol{b} = 0.5, \quad \boldsymbol{l} = 0.5$

d	1	2.142	3.585
$\hat{p}_1$	0.609	0.47	0.34
$\hat{p}_2$	0.609	0.47	0.34
p_1^C	0.573	0.358	0.197
p_2^C	0.573	0.358	0.197
L^C	0.13	1.07	3.73
L_R^C	0.13	1.07	1.61
L_I^C	0	0	2.11
$p_1^N = p_2^N$	0.665	0.48	0.31
L^N	0.33	0.0	2.93
L_R^N	0.33	0.0	0.07
L_I^N	0	0	2.85

Table A7 $\boldsymbol{b} = 0.2, \quad \boldsymbol{l} = 0.75$

d	1	2.142	3.585
$\hat{p}_1$	0.996	0.708	0.595
$\hat{p}_2$	0	0.708	0.595
p_1^C	0.99	0.593	0.425
p_2^C	0	0.593	0.425
L^C	0.04	5.11	4.5
L_R^C	0.04	0.99	1.84
L_I^C	0	4.18	2.66
$p_1^N = p_2^N$	0.942	0.834	0.658
L^N	3.19	3.78	2.73
L_R^N	3.19	1.39	0.28
L_I^N	0	2.39	2.44

Table A8 $\boldsymbol{b} = 0.2, \quad \boldsymbol{l} = 0.25$

d	1	2.142	3.585
$\hat{p}_1$	0.694	0.552	0.41
$\hat{p}_2$	0.694	0.552	0.41
p_1^C	0.676	0.448	0.248
p_2^C	0.676	0.448	0.248
L^C	0.01	0.39	0.85
L_R^C	0.01	0.39	0.85
L_I^C	0	0	0
$p_1^N = p_2^N$	0.779	0.599	0.395
L^N	0.34	0.08	0.00
L_R^N	0.34	0.08	0.00
L_I^N	0	0	0

---

[1] See Ulph (1997) for a survey.

[2] See, for example, Katsoulacos and Xepapadeas (1996), and Petrakis and Poyago-Theotoky (1997).

[3] See for example, A. Ulph (1993), A. Ulph (1996), A. Ulph and D. Ulph (1996), and D. Ulph (1994).

[4] The exception is Petrakis and Poyago-Theotoky (1997). However, although they allow for R&D co-operation, they assume that governments are unable to implement environmental policies such as pollution taxes. Thus they are unable to address the central issue of this paper – the effects of environmental policies on RJV performance.

[5] Of course concern is also sometimes expressed that RJVs may use the ability to cooperate on R&D decisions to promote anti-competitive practices in the output market. Nevertheless RJVs are widely thought to be beneficial on balance, and many governments promote their formation through reducing the ventures' antitrust liabilities, and, sometimes, by subsidising R&D undertaken through an RJV. For an account of recent work on this topic, see, for example, Poyago-Theotoky (1997), for a collection of recent papers.

[6] These may be actual or anticipated environmental regulatory policies. Scott (1996) reports evidence that RJV formation takes place in response to both actual and anticipated regulation.

[7] In particular emissions technology.

[8] The discussion that follows is based heavily on the analysis in Ulph and Katsoulacos (1998).

[9] Of course not every paper suffers from every one of the weaknesses we identify. However most of them arise in the paper by d'Aspremont and Jacquemin (1988) which has become a classic reference in the literature

[10] If governments have no output instrument then we are confined to second-best optima

[11] Each firm operates its own lab in the non-cooperative equilibrium.

[12] While these papers do not allow for the possibility of an R&D subsidy, it is clear that in this framework such a subsidy will not in general enable governments to achieve a second-best outcome under either cooperation or non-cooperation. This is particularly true when the social optimum involves closing a lab. An R&D subsidy may encourage an RJV to keep a lab open that it would otherwise have closed. Thus the Hinloopen result will not generalise to this case.

[13] This reflects the assumption mentioned above - that research discoveries are perfect substitutes. This is the opposite extreme to most of the literature on RJVs which has focused on the case of complementary research discoveries.

[14] It is worth noting that, as $b \to 1, \quad g(p) \to -\log(1-p) - p$.

[15] In the terminology used by Katsoulacos and Ulph (1998a), the research discoveries are perfect substitutes.

[16] We show in Katsoulacos and Ulph (1998a) that there is no loss of generality in reducing the options to just two.

[17] This ignores the possibility that there may be some involuntary information leakage whereby the emissions of the firm that has not discovered are $1+q.\underline{d}, \quad 0<\underline{d}<1$.

[18] This ignores the possibility that the firm that has not discovered may have limited capacity to utilise the information it receives, so its costs of production are $1+q.\bar{d}, \quad 0<\bar{d}<1$.

[19] For each firm this is defined as the difference between the payoff (in terms of profits or welfare) if both firms innovate and the payoff if the other firm alone innovates.

[20] For each firm this is defined as the difference between the payoff if it alone discovers and the payoff if neither discovers.

[21] Higher values of this parameter resulted in outcomes where firms were innovating almost surely most of the time, while lower values of this parameter produced very low R&D probabilities. As we will see, this parameter produces quite a wide range of R&D probabilities as other parameters varied.