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TRADE, STRATEGIC INNOVATION AND STRATEGIC ENVIRONMENTAL POLICY – A GENERAL ANALYSIS

Alistair Ulph and David Ulph

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Centre for Economic Policy Research
25–28 Old Burlington Street
London W1X 1LB
Tel: (44 71) 734 9110

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ABSTRACT

Trade, Strategic Innovation and Strategic Environmental Policy – a General Analysis*

There has been much debate recently about the nature of environmental policy that will be set by governments concerned about the competitive advantage their industries might obtain in a world of fierce trade competition. Some claim governments will set environmental policies that are too lax, while others claim that policies will be excessively tough (in order to spur firms to innovate). Both these claims relate to the possibility that governments may distort their environmental policies for strategic reasons, and to test these claims requires modelling environmental policy in a world of imperfect competition where there are strategic gains to governments trying to manipulate markets through their environmental policies, and to producers trying to manipulate markets through their R&D decisions.

There is now a considerable literature which adapts the literature on strategic international trade to include environmental policy, but this literature suffers from some limitations. Most of the models consider the cases where either only governments act strategically or only producers act strategically. A proper analysis would allow for both sets of agents to act strategically. This is done in Ulph (1993a), and in Ulph (1994). In this paper we provide a more general treatment of the issues. We allow for both governments and producers to act strategically, and for producers' R&D to reduce both costs of production and emissions, but without imposing special functional forms. We show that despite this extra generality the papers by Ulph (1993a) and Ulph (1994) effectively encompass the entire set of qualitative results that can be obtained.

JEL Classification: F12, F13, H23, Q28
Keywords: environmental policy, international trade, imperfect competition, innovation, strategic behaviour

Alistair Ulph
Department of Economics
University of Southampton
Southampton
SO9 5NH
Tel: (44 703) 592 544

David Ulph
Department of Economics
University College London
Gower Street
LONDON
WC1E 6BT
Tel: (44 71) 380 7862

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NON-TECHNICAL SUMMARY

In the debates over the recent extensions of trade liberalization (Uruguay Round, Single European Market, NAFTA) a number of competing claims were made, two of which are the focus of this paper. The first concerns the fear of environmentalists that, in the absence of trade policy instruments, governments might seek to give their domestic producers a competitive advantage by relaxing environmental policies imposed on them. The second is the counter-claim that, far from weakening environmental policies, governments would seek to toughen environmental policy to provide an incentive for their domestic producers to innovate green technologies ahead of their rivals.

Conventional trade theory with competitive markets provides little support for either claim. A more appropriate framework for testing these claims is the world of imperfectly competitive international markets, where governments may indeed have incentives to manipulate the markets through their environmental policies and producers have incentives to manipulate the markets through their R&D policies. There is now a significant literature which addresses these questions, but to date the literature has used rather special models. Thus much of the literature considers only the case where governments distort their environmental policies. In this class of models if producers compete in the product market by setting output rather than price, then, in general, governments will have incentives to weaken their environmental policies. Such studies do not allow for the second claim, however, by ignoring the R&D decisions of producers.

A small number of studies allow for both governments to set their environmental policies strategically and for producers to set their R&D policies strategically. Again the models used have been rather special. Thus some of the papers focus only on the case of *process R&D* where R&D can reduce production costs, but does not affect the pollution caused by production. Other papers focus only on the case of *environmental R&D* where R&D is used to reduce emissions per unit of output, i.e. makes technology 'greener'. These two forms of R&D have rather different implications for environmental policy. If there is only process R&D, then toughening environmental policy raises producers' costs and lowers their incentives to undertake R&D. This means that allowing for process R&D will simply reinforce any incentive for governments to relax environmental policy, since that will reduce the costs of their domestic producers both directly and indirectly through the effect of environmental policy on R&D and hence costs. On the other hand, with environmental R&D toughening environmental policy will have two effects on the incentives to undertake R&D; by raising costs it will again reduce the profitability of doing R&D, but it will increase the *effectiveness* of R&D. Thus there is the possibility that toughening environmental policy will indeed boost the amount of R&D undertaken by domestic producers. It clearly makes sense to allow for both forms of R&D. A second sense in which the papers in this literature have been rather special is that they have employed special assumptions about the nature of demand, cost and R&D functions. A final sense in which the literature has been rather special is in considering only one form of environmental policy instrument.

In this paper we provide a more general treatment of the issues than any of the previous papers in the literature. We allow governments to set environmental policies strategically and consider cases where governments use emissions taxes or emission standards as their instruments; we allow producers to engage in both environmental and process R&D; and we use general functional forms. Three main results emerge.

First, rather surprisingly, when governments use emission taxes, allowing for both process and environmental R&D does not change qualitative results relative to those that arise when producers use only environmental R&D. Second, neither of the claims noted at the beginning holds in general. The reason is straightforward. There are two factors operating on environmental policy. First, there is the direct impact of environmental policy on costs of production, which always gives an incentive to relax environmental policy for conventional 'rent-shifting' reasons; and second, there is the impact of environmental policy on R&D and hence costs, which, as already indicated, is ambiguous. If toughening environmental policy causes domestic firms to do less R&D then this will reinforce the argument for governments to relax environmental policy. But even if tougher environmental policy induces domestic producers to do more R&D, as the second claim presupposed would be the case, this does not mean that governments will want to toughen environmental policy, for there is still the direct rent-shifting argument going in the other direction. If the R&D argument goes in the opposite direction from the rent-shifting argument, however, and is strong enough, then governments may indeed set tougher environmental policies when they act strategically than when they do not act strategically. Finally, in the model used here, governments are more likely to set too tough environmental policies when they use emission standards than when they use emission taxes.

TRADE, STRATEGIC INNOVATION AND STRATEGIC ENVIRONMENTAL POLICY - A GENERAL ANALYSIS

Introduction.

The recent debates over moves to extend trade liberalisation, such as the Uruguay Round, the Single European Market and, especially NAFTA, have featured a number of extreme claims. On the one hand there have been concerns expressed by environmentalists that such moves will damage the environment. One aspect is that the consequent expansion of consumption, production and trade will lead to increased pollution and use of scarce natural resources, unless corrective policies are taken. A second aspect, which will be the focus of this paper, is the fear that in the absence of trade policy instruments, governments may seek to distort their environmental policies in order to protect their domestic economies. In the case of pollution related to production processes and methods (PPM in the language of GATT), this could lead governments to impose too lax a regime of environmental regulation, (so-called "eco-dumping"), for fear that tougher environmental regulation may damage the competitiveness of their domestic economies. This leads to policy suggestions that there should be moves to harmonise environmental regulations across countries, or, if that is not achieved, that countries who impose tighter environmental regulations than their rivals should be able to impose countervailing tariffs on imports from countries with laxer environmental regulations, with tariffs being equal to the difference in abatement costs between the two countries. Not surprisingly, such policies frequently find favour with industries in the traded sector.

On the other hand, Michael Porter (1991) has argued that governments could provide a competitive advantage to their domestic producers by imposing environmental policies which are tougher than those faced by their rivals, since this will spur industries to innovate greener technologies ahead of their rivals, and enhance the long-run profitability of domestic industry. This view finds considerable support in the US administration, and is also commonly espoused in Germany and Japan. In its extreme form it suggests that environmental regulations are beneficial to both the environment and the economy.

Economists have argued that careful economic analysis does not lend unqualified support to either set of claims (see Low (1992) for a useful collection of papers addressing some of these issues). Turning first to the environmentalists' concerns, economic analysis shows that with perfectly competitive markets, a small country whose production-related pollution caused only local, not transboundary, damages, would have no incentive to distort its environmental policies in the way suggested (see, for example, Long and Siebert (1989)). If there were perfectly competitive markets, but a country had market power, then in the absence of trade instruments governments will have incentives to distort their environmental policies. But, as Rauscher (1994), among others, has shown a country which is an exporter of a pollution intensive good, because it is relatively well endowed with environmental resources, will want to impose environmental regulations which are tougher than the first-best rule (set emissions so that marginal abatement cost equals marginal damage cost), while the importing country will set laxer environmental policies. So while some countries will be too lax, others will be too tough; thus not all countries will engage in ecodumping and there can be no presumption that in aggregate environmental quality will be worse than first best.

To make sense of the concern about eco-dumping it is natural to turn to models of imperfect competition, and there are now a number of studies which have extended the literature on strategic international trade (see Helpman and Krugman (1989)) to consider environmental questions. Barrett (1992), Conrad (1993) Kennedy (1993), Nannerup (1992) and Rauscher (1994) have all developed variants of the basic Brander and Spencer (1985) model of oligopolistic markets where a number of producing firms located in different countries and selling into other markets compete in Cournot fashion, and show that indeed there can be "rent-shifting" incentives for governments of all producing countries to set targets for emissions that are lower than would be warranted by the first best rule in order to give their domestic producers a strategic advantage in the output market. While this would appear to provide a model which rationalises the environmentalists' concern about ecodumping, the difficulty is that this result is not at all robust, so it is possible to build equally plausible models in which governments set too tough environmental policies; for example, changing from Cournot to Bertrand competition would generate this effect (Barrett (1992); see also Ulph (1993b) for a survey of other cases).

The above models of strategic environmental policy allow only for the case where governments alone act strategically. Ulph (1992a,b) studies the case where only producers act strategically through their choice of R&D or capital, but governments have fixed targets for emissions, and so do not choose these strategically. However, these papers make the important point that the environmental policy instruments (e.g. taxes or standards) chosen by governments can have significantly different impacts on the strategic behaviour of producers and hence on profits and welfare.

To be able to analyse the Porter claim, and to provide a fuller analysis of the environmentalists claims, it is clearly necessary to have a model in which there is strategic behaviour by both producers and governments. Ulph (1993a) considers such a model, but in that paper innovation by producers is designed solely to reduce costs of production, but has no impact on emissions or abatement. Ulph (1994) also allows for strategic behaviour by both producers and governments, but in this paper innovation is designed solely to reduce emissions per unit of output. These different forms of innovation are important; thus Ulph (1993a) shows that with both governments and producers acting strategically, environmental policy by governments will be too lax, but Ulph (1994) shows that environmental policy may be either too tough or too lax. This suggests that when innovation concerns environmental technology, there is the possibility of confirming the Porter claim, but it is important to note that this is only a possibility, and the opposite claim can be a possible outcome.

Other differences between these two papers are that Ulph(1993a) shows that his conclusion that environmental policy will be too lax applies both in the case where governments use taxes as the environmental instrument and in the case where they use standards, whereas Ulph(1994) focuses on taxes alone. However Ulph(1993a) derives his conclusions in the context of a model that employs specific functional forms, whereas Ulph(1994) uses general functional forms.

Bradford and Simpson (1993) allow for strategic behaviour by both governments and firms and for R&D to reduce both costs of production and emissions. However in the first part of their paper the responses of firms' costs to R&D and environmental taxes are not derived from optimising behaviour of firms, which means they cannot use the implications of such behaviour to derive predictions about the impact of environmental policy; in the second part of their paper they do use such optimising behaviour, but impose particular functional forms which, as we shall see, severely limit the generality of their results.

In this paper we shall provide a more general treatment of strategic behaviour by producers and governments than any available in the literature so far. In addition to allowing both governments and producers to act strategically, we allow for strategic innovation by producers to reduce both costs of production and emissions; the models we use employ general functional forms with all decisions being derived optimally in a three-stage game. We also explore separately the case where taxes are the environmental instrument and the case where governments use standards to control emissions. Within this more general framework we can thus assess just how special and restrictive the existing analysis is.

We show that when governments use taxes to control emissions the qualitative results obtained in the papers by Ulph (1993) and Ulph(1994) essentially encompass all the results that can be obtained. More precisely we show that when firms undertake both environmental and process R&D then all the results we obtain are precisely those obtained by Ulph (1994) where firms undertake only environmental R&D. The intuition is this. As we will see, it is crucial to know whether an increase in a country's environmental tax causes the costs of firms located in that country to rise or fall. In Ulph (1994) it was shown that this depended on whether the increase in environmental R&D induced by the tax was more or less than enough to offset the direct effect on costs of the tax increase, and this in turn depends on the precise form of the relationship between emissions and R&D. Adding in process R&D does nothing to alter this. If, ignoring process R&D, costs rise as a result of the tax, this will cause firms to lose market share. But this will lower the incentive to undertake process R&D which will just exacerbate the effect of the tax on firms' costs. Conversely if, ignoring process R&D, firms' costs were to fall when the tax rose, this will increase market share, thus increasing the incentive for process R&D, which will simply reinforce the effects produced by the analysis in which there is only environmental R&D.

Turning to standards, we show that whereas Ulph(1992a, 1992b, !993a) obtains the unambiguous prediction that standards will be too lax when governments act non-cooperatively, in the more general setting standards may under some circumstances be too tough. This only arises however when an extreme form of the porter hypothesis holds - namely that when governments set tougher standards this so encourages additional R&D by firms that their total output can expand.

There are two caveats. First we consider a model in which there is no abatement activity by firms. This is particularly crucial in the case of standards since then, as we will show, there is no scope for strategic behaviour by firms, and governments ignore any transboundary pollution when setting standards independently. Thus the analysis applies to a particular class of pollution problems like global warming where there is no significant abatement technology. Second, it can be argued that this paper, like most of the papers cited so far, do not provide a proper context for analysing the Porter claim, since they employ *non-tournament* models of R&D competition in which there is no possibility of one country's producers gaining an advantage by acquiring a new technology to which their rivals cannot get access. To study such a possibility requires the use of tournament models of R&D. Ulph (1994) provides a preliminary analysis of such models.

The structure of this paper is as follows. Section 1 sets out the model to be employed. Sections 2 & 3 derive the results for the case of taxation. Section 4 undertakes the analysis for standards, while Section 5 summarises the findings and gives directions for future research.

Section 1: The Basic Model

There is a single industry in which there are just two firms, each located in a different country. Production in each of the two firms produces a certain amount of emissions per unit of output. The emissions generated by each firm can damage not just the country in which that firm is located but the other country as well.

We assume that in the short-term there is no way in which firms can reduce total emissions other than through cutting back output. However in the longer-term firms can undertake R&D which leads to new technologies which have a lower level of emissions per unit of output. We will refer to this as *environmental R&D.* Of course firms will also want to undertake R&D for the traditional reasons of lowering costs or improving product quality. Here we will assume that this other R&D leads to process innovation which lowers unit costs. We will refer to this as *process R&D.*

In the absence of government policy firms would have no incentive to undertake *environmental R&D*, so all R&D would be *process R&D.* If governments implement environmental policy then firms have incentives to undertake both types of R&D, and both will be affected by the nature and extent of environmental policy imposed by governments.

As is common in this literature we take it that international trade agreements rule out the use of any explicit R&D subsidy, and so governments cannot manipulate the strategic behaviour of firms in their country through this channel. However since governments are allowed to implement environmental policy, and since key components of firms' strategic behaviour will be influenced by such policy, we are interested in how the strategic competition between firms affects the type of environmental policy implemented by governments. Accordingly we assume that each country is run by a separate government. In this paper we assume that the policy instruments that each government uses to control emissions is an emissions tax which is imposed at a constant rate on every unit of emissions produced within that country. In a subsequent paper we investigate the case where governments use standards as the environmental policy instrument.

The model is set up as a three stage game. In the third stage each firm chooses a level of output conditional on its unit costs of production, on the output of the other firm, and on any upper limit on output imposed by standards. Unit costs of each firm depend on the level of any emissions tax in force in its country and on both the production and environmental technologies employed by the firm. We determine the Cournot equilibrium in outputs.

In the second stage each firm chooses the amounts of both *environmental R&D* and *process R&D* it wishes to undertake. Again we assume that each firm chooses its R&D levels taking as given those of the other firm, and we hence determine the Nash equilibrium levels of both types of R&D by both firms.

Finally, in the first stage each government chooses either the tax rate on emissions it wishes to impose. The objectives of governments will be the level of welfare in each of the two countries. Welfare will be measured as profits minus damage . So we will be ignoring consumer surplus issues. We are interested in comparing the tax rates that would be imposed if each of the two governments acts independently with those that would arise if they act co-operatively.

Throughout the paper we will assume that the two countries are symmetric, and so focus on symmetric equilibria. We will use symmetry to focus most of the analysis on the behaviour of firm 1, with that of firm 2 following by symmetry.

As is usual, we set the model out and solve it recursively starting with the third stage output game, then the second stage R&D game and finally the first stage tax game. In the next section we will take the taxe rates as given and work out all the comparative static implications of changes in these rates that arise in stages two and three. Then in Section 3 we will work out the non-cooperative and cooperative tax equilibria. Section 4 carries out the analysis for standards.

Section 2. Comparative Static Analysis for Taxes

We start by examining the output game.

2.1 Stage 3: Equilibrium in the Output Market

Firm i faces a revenue function $R(y_1, y_2)$, where y_i is the output of firm . We assume $R(0, y_2) = 0$; $R_1(0, y_2) > 0$; $R_{11}(.) < 0$; $R_2(y_1, y_2) < 0$ if $y_1 > 0$; $R_{12}(.) < 0$.

Given the output of firm 2 and unit costs c_1, firm 1 chooses y_1 to

$$\text{MAX} \quad R(y_1, y_2) \; - \; c_1 . y_1$$

Assuming that equilibrium output is positive, the first-order condition is

$$R_1 \; = \; c_1$$

The Cournot equilibrium output of firm 1 is $y_1 \; = \; \eta(c_1, c_2)$.

We will assume that we have the conventional results of Cournot equilibrium theory: $\eta_1 < 0$; $\eta_2 > 0$; $\eta_1 + \eta_2 < 0$. Thus an increase in each firm's costs causes its equilibrium output to fall, and that of its rival to rise, with the own effect dominating the cross effect, so total industry output falls.

By inserting the equilibrium levels of output back into the expression for profits, we can also generate the profit function for firm 1, $\pi(c_1, c_2)$, which we assume has the conventional properties:

$$\pi_1 = -y_1 + R_2 . \eta_2 < 0; \quad \pi_2 > 0; \quad \pi_{11} > 0; \quad \pi_{12} < 0. \qquad (1)$$

There are a number of important points to note here.

(i) Profits are decreasing in own costs. Moreover the marginal reduction in profits of an increase in costs is made up of two parts: the *non-strategic part* whereby the loss in profits is directly proportional to output; the *strategic part* which shows that part of the loss in profits comes from the expansion in market share by the rival firm. It is this *strategic* component that leads firms to over invest in R&D in conventional 2-stage models of strategic investment. As we will see, this plays an important role later on in determining government behaviour.

(ii) Profits are *convex* in own costs, so the lower are a firm's costs initially, the greater are the gains in profits from a unit reduction in costs.

(iii) The higher are the rival firm's costs, the greater are the gains in a firm's profits from a reduction in its own costs. This just reflects the fact that the higher unit costs of the rival firm, the larger is a firm's equilibrium output, and so the greater its gain from lowering costs.

2.2 Stage 2: Strategic R&D Equilibrium

We now specify unit costs of country i as

$$c_i = a(x_i) + t_i . e(z_i) \qquad (2)$$

where a is the minimum cost of production per unit of output; x_i is the amount of *process R&D* undertaken by firm; t_i is the emissions tax imposed by country i; e is emissions per unit of output by firm i; and z_i is the amount of *environmental R&D* undertaken by firm i.

We assume $a'(.) < 0$; $a''(.) > 0$; $e'(.) < 0$; $e''(.) > 0$. So both types of R&D are effective in lowering costs/emissions but are subject to diminishing marginal productivity.

Firm 1 then takes the R&D (and hence the unit costs) of firm 2 as given and chooses x_1 and z_1 so as to maximise profits:

$$\pi\left[a(x_1) + t_1 e(z_1), c_2\right] - x_1 - z_1 \qquad (3)$$

We can set this up as a two-step problem.

Step 1

Given a total amount, r, to be spent on R&D, we can work out how to spend this on the two types of R&D so as to minimise unit costs of production. Accordingly define

$$c(r,t) \equiv MIN \quad a(x) + te(z) \quad \text{s.t. } x + z \le r$$

and let $x = X(r,t)$, $z = Z(r,t)$ be the solutions to this problem.

The comparative statics are straightforward, but we need to distinguish three separate cases:

Case (i) No Environmental R&D: $x > 0$, but $z \equiv 0$ on some neighbourhood.

This is essentially the case considered by Ulph (1993) where all R&D is assumed to be *process R&D*. In this case

$$X(r,t) = r, \quad X_r \equiv \frac{\partial X}{\partial r} = 1, \quad X_t \equiv \frac{\partial X}{\partial t} = 0;$$

$$c(r,t) = a(r) + te(0), \quad c_r \equiv \frac{\partial c}{\partial r} = a'(r) < 0, \quad c_t \equiv \frac{\partial c}{\partial t} = e(0) > 0,$$

$$c_{rr} \equiv \frac{\partial^2 c}{\partial r^2} = a''(r) > 0, \quad c_{rt} \equiv \frac{\partial^2 c}{\partial t \partial r} = 0$$

Thus costs are decreasing and convex in total R&D, are increasing in the tax rate, but the tax has no effect on the marginal effectiveness of R&D in lowering costs.

Case (ii) No process R&D: $z > 0$, but $x \equiv 0$ on some neighbourhood

This is essentially the case considered by Ulph (1994) where all R&D takes the form of *environmental R&D*. In this case

$$Z(r,t) = r, Z_r \equiv \frac{\partial Z}{\partial r} = 1, Z_t \equiv \frac{\partial Z}{\partial t} = 0;$$
$$c(r,t) = a(0) + te(r), c_r = te'(r) < 0, c_t = e(r), c_{rr} = te''(r) > 0; c_{rt} = e'(r) < 0$$

Thus costs are decreasing and convex in total R&D, are increasing in the tax rate, but an increase in the tax rate now increases the marginal effectiveness of R&D in lowering costs.

Case (iii) Both Types of R&D: $x > 0, z > 0$

This is the more general case which collapses to the previous two in particular circumstances. So, for example, a necessary (though not sufficient) condition for this case to arise is that $t > 0$.

Here

$$0 < X_r, \quad 0 < Z_r, \quad X_r + Z_r = 1; \quad X_t = -Z_t < 0,$$

and

$$c_r = a'[X(r,t)] = te'[Z(r,t)] < 0; \quad c_t = e[Z(r,t)];$$
$$c_{rr} = a''(X).X_r = te''(Z).Z_r > 0; \quad c_{rt} = a''(X).X_t = e'(Z).Z_r < 0.$$

Thus as in (ii) costs are decreasing and convex in total R&D, and an increase in the tax rate raises costs but also increases the marginal effectiveness of R&D in lowering costs.

Step 2

r is now chosen so as to

$$MAX \quad \pi\left[c(r,t), c_2\right] - r$$

The <u>assumed</u> interior solution to this is characterised by

$$\phi(r,t,c_2) \equiv \pi_1\left[c(r,t), c_2\right].c_r(r,t) = 1$$

and will be denoted by $r = R(t, c_2)$.

The second-order condition for a maximum is $\phi_r < 0$, and so we have the following comparative static results:

$$\left[-\phi_r\right].R_c = \phi_c = \pi_{12}.c_r \tag{4}$$

and

$$\left[-\phi_r\right].R_t = \pi_{11}.c_r.c_t + \pi_1.c_{rt} \tag{5}$$

where, $R_c \equiv \dfrac{\partial R}{\partial c_2}$ etc.

Given our assumption (1) it follows from the results established above that in all three cases the RHS of (4) is positive. Since firm 2's costs will also be a decreasing function of its total R&D level and an increasing function of the tax rate in country 2, we have:

Result 1 Firm 1's total R&D spending is a decreasing function of the total R&D spending by firm 2, and an increasing function of the tax rate imposed in country 2 .□

Thus if we think of each firm having a reaction function giving its total R&D spending as a function of the total R&D spending of the other firm, then Result 1 shows these reaction functions are downward-sloping.

Moreover an increase in the tax rate in one country unambiguously increases (shifts outward) the reaction function of the firm in the other country. The intuition is straightforward: anything that happens in country 2 to reduce firm 2's costs will reduce firm 1's output and so lower its incentive to reduce its costs.

Given our assumptions, and the results established above, we see that the first term on the RHS of (5) is negative, while the second is zero in Case (i), but positive in Cases (ii) and (iii).

We then have:

Result 2 (i) If firm 1 undertakes no *environmental R&D* then $R_t < 0$ - i.e. an increase in the tax rate in country 1 unambiguously lowers firm 1's R&D (shifts firm its reaction-function inwards towards the origin).

(ii) If firm 1 does undertake some environmental R&D then an increase in the tax rate in country 1 may either increase or reduce firms 1's R&D (shift its reaction function outwards or inwards) .□

Once again the intuition is straightforward. An increase in the tax-rate in country 1 increases the costs of firm 1, which reduces the marginal increase in profits to be had from a unit reduction in costs. When the firm does no *environmental R&D* then this is the only effect. Result 2.(i) generalises the result in Ulph(1993). However, when firm 1 does undertake *environmental R&D* then, as we have seen, an increase in the tax-rate in country 1 also increases the effectiveness of R&D in lowering costs, and this effect operates to increase the incentive to spend on R&D. The overall effect is ambiguous.

So far we have derived firm 1's reaction function giving its total R&D as a function of the total R&D undertaken by firm 2. We can combine this with the reaction function for firm 2 and so determine the Nash equilibrium levels of R&D spending for each of the two firms.

These equilibrium R&D levels are given as solutions to the equations

$$r_1 = R[t_1, c(r_2, t_2)] \qquad (6)$$

and

$$r_2 = R[t_2, c(r_1, t_1)]. \qquad (7)$$

Denote the equilibrium R&D level of firm i by $r = \rho(t_1, t_2)$.

In what follows we will need comparative static results showing how this equilibrium is affected by the two tax rates. Since we will eventually be considering a symmetric equilibrium where $t_1 = t_2$, in what follows we will confine the derivation of comparative static results to cases where we start from any such initially symmetric situation.

Notice that in such a situation the slope of each firm's reaction function is given by $R_c.c_r$, hence if we let $\Delta = 1 - [R_c.c_r]^2$, it follows from standard duopoly theory that the condition for the Nash equilibrium R&D levels to be stable is that $\Delta > 0$. By differentiating through (6) and (7) it is then straightforward to show that

$$\Delta.\rho_1 = R_t + (R_c)^2.c_r.c_t \qquad (8)$$

where $\rho_1 \equiv \dfrac{\partial \rho}{\partial t_1}$

The interpretation is straightforward. The first term on the RHS of (8) tells us what happens to firm 1's reaction function as the result of an increase in t_1. As we have seen, this can be positive or negative. The second term reflects what happens to firm 2's reaction function because of the increase in t_1. We know that this shifts outward, and so this must lower firm 1's equilibrium R&D, which is reflected in the fact that this second term on the RHS of (8) is negative.

We also have

$$\Delta.\rho_2 = R_c.c_t + R_c.c_r.R_t \qquad (9)$$

where $\rho_2 \equiv \dfrac{\partial \rho}{\partial t_2}$.

The first term on the RHS of (9) is positive and reflects the fact that an increase in t_2 will shift out firm 1's reaction function. The sign of the second term is the negative of the sign of R_t and simply reflects the effect on firm 1's equilibrium R&D of whatever effect the increase in t_2 has on firm 2's reaction function.

We therefore have the following

Result 3. If $R_t \leq 0$, then $\rho_1 < 0$, $\rho_2 > 0$. □

From Result 2(i) it therefore follows that when there is no environmental R&D an increase in the tax reduces the equilibrium R&D of firm 1 and increases that of firm 2 - a generalisation of the result in Ulph (1993).

Notice that, by symmetry (9) also tells us the effect of an increase in t_1 on the equilibrium R&D of firm 2. That is

$$\Delta.\frac{\partial r_2}{\partial t_1} = \Delta.\rho_2 = R_r.\left[c_t + c_r.R_t\right] \qquad (10)$$

While these comparative static results are of central interest, it is also important to know how taxes affect costs, since this is the key way in which environmental taxes affect the competitiveness of firms in the product market. To examine this, notice that firm 1's costs in the R&D equilibrium are given by the function

$$c_1 = \gamma(t_1, t_2) \equiv c\left[\rho(t_1, t_2), t_1\right] \qquad (11)$$

Differentiate (11) and use (8) to get

$$\Delta.\gamma_1 = c_t + c_r.R_t \qquad (12)$$

where $\gamma_1 \equiv \dfrac{\partial \gamma}{\partial t_1}$

Thus, the sign of the overall impact of the increase in t_1 on firm 1's costs can be determined by its direct effect on costs and on firm 1's R&D taking as given the costs of firm 2.

Notice that from (9), (10) and (12) we therefore have

$$R_r.\gamma_1 = \rho_2 = \frac{\partial r_2}{\partial t_1} \qquad (13)$$

This just tells us if, overall, an increase in t_1 drives up firm 1's costs then this will induce firm 2 to do more R&D. Thus there is a one-to-one link between how the tax rate in country 1 affects the profitability of firm 1 and how it affects the R&D done by firm 2.

It also follows from (11) that

$$\gamma_2 = c_t . \gamma_1 \tag{14}$$

where $\gamma_2 \equiv \dfrac{\partial \gamma}{\partial t_2}$

Once again it follows by symmetry that (14) also gives the effect on firm 2's costs of an increase in t_1. Thus (14) tells us that an increase in t_1 always affects firm 1's costs and firm 2's costs in opposite ways.

We can summarise these results in

Result 4. $\quad \text{sign}(\gamma_1) = \text{sign}(\rho_2) = -\text{sign}(\gamma_2)$

From Results 2(ii) and 3 we then obtain

Corollary. In Case (i) where firms do **no** *environmental R&D* then an increase in tax in country 1 unambiguously lowers R&D in country 1, increases costs in country 1, increases R&D in country 2 and therefore lowers costs in country 2.

This corollary just generalises all the results obtained in Ulph (1993) for particular functional forms.

It is clear then from (9), (10), (12), (13) & (14) that a key term in all the comparative static analysis is

$$K \equiv c_t + c_r . R_t \tag{15}$$

By substituting (5) into (15), it is straightforward to show that

$$[-\phi_r]K = [-\pi_1].k$$

where

$$k = c_t . c_{rr} - c_r . c_{rt} \tag{16}$$

Hence everything just depends on the sign of k.

If we go back to the three cases discussed above we have:

Case (i) $\quad k = e(0).a''(r) > 0$ and so $\rho_2 > 0, \gamma_1 > 0, \gamma_2 < 0.$

Case (ii) $\quad k = t\left[e''(r).e(r) - (e'(r))^2\right]$

Case (iii) $\quad k = t.\dfrac{\partial Z}{\partial r}.\left[e(Z).e''(Z) - (e'(Z))^2\right]$

Hence as we have already noted in the Corollary to result 4, we get unambiguous comparative static predictions in Case (i) where there is no environmental R&D.

However in Cases (ii) and (iii) everything depends on the properties of the $e(.)$ function.

The following result was proved in Ulph (1994)

Result 5

A) If $e(z) = e_0.e^{-\alpha z}$ then $k = 0$ and so $\rho_2 = \gamma_1 = \gamma_2 = 0$.

B) If $e(z) = e_0(1+z)^{-\alpha}$ then $k > 0$ and so $\rho_2 > 0, \gamma_1 > 0, \gamma_2 < 0$.

C) If $e(z) = e_0\left(1 - \frac{z}{\alpha}\right)^2$, then $e(.)$ is positive and decreasing as long as $z < \alpha$.

Hence provided , is sufficiently large any solution will lie in this interval. Moreover throughout this interval $k < 0$, and so $\rho_2 < 0, \gamma_1 < 0, \gamma_2 > 0$. □

Result 5 A) is precisely the result obtain by Simpson and Bradford (1993) in their special example which uses a negative exponential R&D function. They show that in this case the tax has no effect on rival's R&D, nor on equilibrium costs. All that is happening is that the increased R&D induced by the increase in tax is sufficiently large that costs remain unaffected. Since this has not changed the outcome of output competition in Stage 3, there is no incentive for firm 2 to change its R&D decision, and so its costs too remain unaffected by the increase in tax.

Notice that in terms of the comparative static predictions Result 5B is in essence identical to that which arises in Case (i) where there is no environmental R&D. This is because what is happening is that the increase in environmental R&D brought about by the increase in tax is insufficent to offset the direct effects on costs of the tax increase so the overall effect of the tax is to drive up costs of firm 1. Case (i) is just a more extreme case where there is no environmental

The thing that is strking about Result 5 is that what we have shown is that in terms of the general qualitative comparative static predictions about how taxes affect costs and rival R&D behaviour Cases (ii) and (iii) are effectively identical, and so absolutely nothing is added to the comparative static analysis in Ulph (1994) by moving to the more general case where firms can undertake both types of R&D. The intuition is this. Suppose as in Ulph (1994) we were to ignore process R&D, and were to work out the overall effect of a an increase of the tax in country 1 on firm 1's costs (taking account of the induced impact on environmental R&D). Once we know the change in costs we will know the change in the incentive to do process R&D - and any effect this has will just reinforce the effect we have already worked out.

The final comparative static result we want to prove in this section is:

Result 6 If $k = 0$ then $\rho_1 = R_t = -\dfrac{c_t}{c_r} > 0$.

Proof: From (15) and (16), $k = 0 \Rightarrow K = 0 \Rightarrow R_t = -\dfrac{c_t}{c_r} > 0$. From (8)

$$\Delta.c_r.\rho_1 = c_r.R_t + c_t.\left[c_r.R_c\right]^2 = c_t\left\{-1+\left[c_r.R_c\right]^2\right\} = -\Delta.c_t \quad \Rightarrow \quad \rho_1 = -\frac{c_t}{c_r}.$$

The intuition is straightforward. When $k = 0$ then the tax has no effect on the rival's R&D and hence costs, and so, from (6), the effect on firm 1's R&D is just the direct effect. However, we know that costs of firm 1 are unaffected, so R&D must rise by enough to offset the direct effect on costs of the increase in tax.

Having understood all the comparative static properties, we can now turn to an examination of how governments set taxes in Stage 1 of the model.

Section 3 Stage 1: Equilibrium Tax Rates

As indicated in the previous section, the welfare objective of each government is profits minus environmental damage. Notice, however, that since taxes are a pure transfer within the economy, the profits that will be of interest are gross profits before tax. As in the previous analysis, we will be invoking symmetry, and so will conduct the analysis solely in terms of the behaviour of the government in country 1.

We also need to distinguish the case where governments set taxes non-cooperatively (unilaterally) from that in which they set the taxes cooperatively.

3.1 Governments Set Taxes Non-Cooperatively

It turns out to be helpful to distinguish the three separate cases considered in Stage 2.

3.1.1 Only Process R&D

Here the welfare function for country 1 is

$$W = R(y_1, y_2) - a(r_1) - r_1 - D[e(0)y_1 + \theta e(0)y_2]$$

where $D(E)$ is the damage suffered by country 1 from the total emissions it receives, and $\theta, 0 \le \theta \le 1$ is an environmental spillover parameter indicating the extent to which emissions generated in country 2 affect country 1.

The first-order condition for the optimal tax for country 1 is therefore

$$W_1 \equiv \frac{\partial W}{\partial t_1} = [R_1 - a - D'.e(0)]dy_1 + [R_2 - \theta D'.e(0)]dy_2 - [a'.y_1 + 1]dr_1 = 0 \qquad (17)$$

where dy_i (dr_1) is the total change in output by firm i (R&D by firm 1) brought about by the increase in t_1

From the analysis conducted in Stage 2 we have

$$dy_1 = \eta_1\gamma_1 + \eta_2\gamma_2 = [\eta_1 + \eta_2 c_r].\gamma_1 \equiv \xi_1.\gamma_1, \text{ where } \xi_1 < 0;$$

$$dy_2 = \eta_1\gamma_2 + \eta_2\gamma_1 = [\eta_1 c_r + \eta_2].\gamma_1 \equiv \xi_2.\gamma_1, \text{ where } \xi_2 < 0;$$

$$dr_1 = \rho_1.$$

If we use insert the first-order conditions for the maximisation of profits w.r.t. output and R&D then (17) becomes

$$[t - D'].[(-\xi_1.e(0))\gamma_1] = [R_2 - \theta D'e(0)].[\xi_2\gamma_1] - [R_2\eta_2 c_r].\rho_1 \tag{18}$$

From the analysis conducted in Stage 2 we know that in Case (i) an increase in t_1 unambiguously discourages R&D by firm 1 (because all it does is raise costs) while for precisely the same reason it encourages R&D by firm 2, and hence increases firm 1's costs so $\rho_1 < 0; \gamma_1 > 0$.

It therefore follows that whether the tax is above or below marginal damage depends entirely on the sign of the RHS of (18). The two terms in this expression have an easy interpretation.

The first term gives what we will call the *rival output effect* of the tax. It is negative and shows the loss to country 1 arising from an expansion in output in country 2 induced by the increase in t_1. This loss arises for two reasons. The first is a strategic loss of profits from the expansion in market share by firm 2, and the second is any additional environmental spillovers as firm 2 expands output.

The second term is what we will call the *strategic over investment effect*. This is positive and reflects the fact that because firm 1 will over invest in R&D for strategic reasons, then because the environmental tax has the effect of reducing R&D it is correcting the distortion produced by imperfect competition, and this is beneficial.

While it might seem that the overall effect is indeterminate, it is important to realise that the fact that firm 1 is over investing in R&D is reflected in firm 2's response to the costs of firm 1. It turns out that by substituting the expressions for ξ_2 and γ_1 into (18) we get, after some re-arranging,

$$\begin{aligned}(t - D')[(-\xi_1 e(0))\gamma_1] &= R_2(\eta_1 c_r)(\gamma_1 + c_r) - \theta D'e(0)\xi_2\gamma_1 \\ &= R_2(\eta_1 c_r)(2c_r\rho_1 + c_t) - \theta D'e(0)\xi_2\gamma_1 < 0\end{aligned} \tag{19}$$

So we have

Result 7 When there is no *environmental R&D* the *non-cooperative* tax is below marginal damage.□

This is precisely the result obtained in Ulph (1993), though we have now proved it using more general functional forms.

3.1.2 Only Environmental R&D

In this case the welfare objective can be written

$$W = R(y_1, y_2) - a(0)y_1 - r_1 - D[e(r_1)y_1 + \theta e(r_2)y_2]$$

Hence

$$W_t = [R_1 - a - D'e].dy_1 + [R_2 - \theta eD'].dy_2 - [1 + yD'e']dr_1 - \theta yD'e'dr_2 \qquad (20)$$

Here the dy_i $(i = 1,2)$ and dr_1 are as above, and $dr_2 = \rho_2 = R_c\gamma_1$. Once again if we use the first-order conditions for profit-maximisation w.r.t. output and R&D we get, after some re-arranging,

$$\begin{aligned}(t - D').[(-\xi_1 e)\gamma_1 + (-e'y)\rho_1] = \\ [R_2 - \theta eD'].(\xi_2\gamma_1) - [R_2\eta_2 c_r].\rho_1 - \theta yD'e'R_c\gamma_1\end{aligned} \qquad (21)$$

Compared to (18) there have been two changes. The first is that the coefficient on $(t - D')$ has an extra term to reflect the fact that it is not just in its output choice but also now in its R&D choice that firm 1's decisions are based on an environmental cost perception reflected in the tax rate rather than the true cost which is marginal environmental damage. The sign of this additional term is the sign of ρ_1. The second is that there is now an additional term on the RHS of (21) which we will call the *spillover via investment effect*. This has the sign of γ_1, and just reflects the fact that country 1 will gain (lose) through the reduction (increase) in environmental spillovers from country 2 to the extent that an increase in t_1 increases (reduces) the R&D done by country 2.

A further change from the previous Case is that, as we saw in Result 4, there are no clear-cut comparative static predictions in Case (ii). So let us consider the various possibilities in turn.

A) $k = 0$ and so $\rho_2 = \gamma_1 = \gamma_2 = 0$.

Here costs and hence outputs are completely unaffected by the tax, as is the R&D done by the rival firm, **so there are absolutely no strategic effects of the tax at all.** Substitute $\gamma_1 = 0$ into (21) and we see that all that remains is the distortionary effect of the tax on R&D decisions (the term in ρ_1 on the LHS of (21)) and the *strategic over investment effect*. Recalling that, from Result 6, $\rho_1 > 0$ (21) becomes

$$t - D' = \frac{R_2.\eta_2.c_r}{e'y} < 0 \qquad (22)$$

so the tax that would be set is unambiguously lower than marginal damage. To see why suppose $t = D'$. Then the tax has no distortionary effect, but because of the *strategic over investment effect* marginal welfare is negative. To reduce investment then, because $\rho_1 > 0$ it is necessary to cut the tax rate.

Thus we have proved

Result 8 When there is no process R&D, and when $k = 0$, then the *non-cooperative tax* is less than marginal damage. ▯

Notice that this result directly contradicts the Porter claim that strategic R&D considerations would lead governments to set excessively tough environmental policy. For here we have a model in which taxes do indeed encourage firms to undertake more R&D, and yet it is optimal for goverments to set taxes which are too lax. The reason is that taxes have no effect on what the rival is doing, so there no incentive to set taxes which might discourage the rival firm. Since the domestic firm is itself choosing R&D for strategic reasons there is no reason for governments to set taxes for strategic reasons. The only reason for setting taxes which differ from marginal damage is to correct any mistakes firms might make in their strategic calculations. As we have seen, the mistake firms make is that they overinvest in R&D - hence the result.

Let us now consider together the two remaining possibilities.

B) $k > 0$ and so $\rho_2 > 0, \gamma_1 > 0, \gamma_2 < 0$.

C) $k < 0$, and so $\rho_2 < 0, \gamma_1 < 0, \gamma_2 > 0$.

We can re-write (21) as

$$(t - D').\left[(-\xi_1 e) + \pi_1 e'.\frac{\rho_1}{\gamma_1}\right] = \left[R_2 - \theta e D'\right].\xi_2 - \left[R_2 \eta_2 D' e'.\frac{\rho_1}{\gamma_1}\right] - \theta y D' e' R_2 \qquad (23)$$

We assume that the coefficient on $(t - D')$ remains positive in which case everything depends on the sign of the RHS of (23). Here the first term - the *rival output effect* - is negative and the third - the *spillover via investment effect* - is positive. The intuition is clear. If, for example, an increase in t_1 increases the output of firm 2 (which is harmful to country 1) then at the same time, given the comparative static results established at Stage 2, it must necessarily encourage firm 2 to do more R&D, which lowers emissions and so benefits country 1.

However the sign of the second term - the *strategic over investment effect* - depends on the sign of $\frac{\rho_1}{\gamma_1}$, and so can be positive or negative which will reinforce one or other of the effects just discussed.

At this level of generality not much can be said about the overall sign of the RHS of (23). However once again, just as we did in going from (18) to (19), we can combine the *rival ouput effect* and the *strategic over investment effect* to get

$$(t - D')\left[(-\xi_1 e) + (\pi_1 e')\frac{\rho_1}{\gamma_1}\right] = R_2(\eta_1 c_r)\left(1 + \frac{c_r}{\gamma_1}\right) - \theta D'(e\xi_2 + ye'R_c)$$

We then have

Result 9 If $\gamma_1 > -c_r$ and if $\theta = 0$ then $t < D'$

3.1.3 Both Process and Environmental R&D Case (iii)

Here the welfare function can be written

$$W = R(y_1, y_2) - a(x_1)y_1 - x_1 - z_1 - D\left[e(z_1)y_1 + \theta e(z_2)y_2\right]$$

Hence

$$W_1 = \left[R_1 - a - D'e\right]dy_1 + \left[R_2 - \theta D'e\right]dy_2 - \left[1 + a'.y_1\right]dx_1 - \left[1 + D'.e'.y_1\right]dz_1 - \left[\theta D'e'y_2\right]dz_2$$

where the dy_i are as before, but now $dx_1 = X_r\rho_1 + X_t; dz_1 = Z_r\rho_1 + Z_t; dz_2 = Z_r\rho_2$.

Using the first-order conditions as before, we now get, after some re-arranging,

$$\begin{aligned}(t - D')\left[(-\xi_1 e)\gamma_1 + (-e'y)(Z_r\rho_1 + Z_t)\right] = \\ \left[R_2 - \theta D'e\right](\xi_2\gamma_1) - \left[R_2\eta_2 c_r\right]\rho_1 - \theta y D'e'Z_r R_c\gamma_1\end{aligned} \qquad (24)$$

Comparing (24) with (21) we see that the only difference is that the coefficient on $(-e'y)$ in the LHS now reflects the fact that not all of firm 1's R&D goes on *environmental R&D*. This is reflected by the inclusion of the term Z_r, where $0 < Z_r < 1$, which shows that only a fraction of any additional total expenditure on R&D will go on *environmental R&D*, and also by the addition of the term Z_t which shows that an increase in t_1 will cause firm 1 to substitute from *process R&D* to *environmental R&D*. In a similar the final term on the RHS of (24) reflects the fact that only a fraction of additional total R&D spending by firm 2 will go on *environmental R&D*.

Thus (24) will reduce to (21) when all R&D is *environmental R&D* and so $Z_r = 1$, $Z_t = 0$. On the other hand (24) reduces to (18) in the case where there is no *environmental R&D* and so $Z_r = Z_t = 0$.

To see what difference this makes over Case (ii) consider again situation

A) $k = 0$ and so $\rho_2 = \gamma_1 = \gamma_2 = 0$.

Now (24) becomes

$$t - D' = \frac{R_2 \eta_2 c_t}{e' y} \cdot \frac{\rho_1}{Z_r \rho_1 + Z_t} \tag{25}$$

From Result 6 we know that $\rho_1 > 0$ so once again $t < D'$

Thus we have proved

Result 10 When there are both types of R&D, and when $k = 0$, then the *non-cooperative tax* is less than marginal damage. □

In situations **B & C** considered above in Case (ii) there is very little change, for, provided the coefficient on $(t - D')$ remains positive, then all we said before about the factors affecting the sign of $(t - D')$ remains unaffected. In particular, Result 9 continues to hold for this case.

Thus the broad qualitative results concerning non-cooperative taxes are exactly the same in Cases (ii) and (iii).

Let us turn then to consider what can be said when governments act cooperatively.

3.2 Governments Set Taxes Cooperatively

Here governments set t_1 and t_2 to maximise the sum of welfare in each of the two countries. Given symmetry, this is formally identical to the problem of setting $t_1 = t_2 = t$, say, and then choosing t to maximise welfare in any one country.

The equilibrium R&D done by each firm is then given by $r(t) = \rho(t, t)$, and it is straightforward to show that

$$r' = \frac{dr}{dt} = \rho_1 + \rho_2 = \frac{R_t + R_c c_t}{\tilde{\Delta}}, \quad \text{where } \tilde{\Delta} = 1 - R_r c_r > 0$$

As discussed above, the first term in the numerator can be positive or negative, since the increase in the domestic tax can either increase or decrease the amount of domestic innovation. However the second term in the numerator is positive reflecting the incentive to greater domestic innovation produced by the increase in the rival firm's costs induced by the increase in the foreign tax. The overall sign is indeterminate at this level of generality.

The equilibrium costs of each firm are given by $c(t) = c[r(t), t]$ and so

$$c' = \frac{dc}{dt} = c_r r' + c_t = \frac{c_t + R_t c_r}{\bar{\Delta}} = (1 + R_r c_r)\gamma_1 .$$

From this it follows that the induced change in outputs by both firms is

$$dy_1 = dy_2 = (\eta_1 + \eta_2)c' = (\eta_1 + \eta_2)(1 + R_2 c_r)\gamma_1 = \bar{\xi}\gamma_1, \quad \text{where } \bar{\xi} = (\eta_1 + \eta_2)(1 + R_2 c_r) < 0 \qquad (26)$$

Having established the comparative static properties of the model we can substitute these into the condition for the optimum tax rate which is

$$\frac{dW}{dt} = \frac{\partial W}{\partial t_1} + \frac{\partial W}{\partial t_2} = 0..$$

If we do this for the general Case (iii) where there is both *environmental R&D* and *process R&D*, we get, after some re-arranging,

$$(t - D')\left[\left(-\bar{\xi}\, e\right)\gamma_1 + (-e'y)(Z_r r' + Z_t)\right] = \left[R_2 - \theta e D'\right]\left(\bar{\xi}\gamma_1\right) - (R_2\eta_2 c_r)r' - \theta y D' e'(Z_r r' + Z_t) \qquad (27)$$

To compare the outcome with that under *non-cooperative tax-setting* behaviour, it will be helpful to once again discuss the three cases in turn.

3.2.1 Only Process R&D: $Z_r = Z_t = 0; \quad \gamma_1 > 0$

Once again we are left with only the *rival output effect* and the *strategic over investment effect*. Compared to the *non-cooperative* situation, the differences are that:

(i) The *rival output effect* is now positive, since raising taxes now reduces rival output, and so both countries would agree to raise taxes above marginal damage for this reason. This is just the argument put forward by Barrett (1992) for the cooperative tax being above marginal damage.

(ii) There is now no guarantee that the *strategic over investment effect* is positive. We know that in Case (i) $R_t < 0$, so there are two offsetting factors determining the sign of r'. Clearly if $r' \leq 0$, we will be able to claim that $t > D'$, and therefore is necessarily above the *non-cooperative* tax. If $r' > 0$ then all we can say is that the two effects have the opposite signs from those have under *non-cooperative* tax setting, but we cannot say much about how the *cooperative* tax compares to either marginal damage or to the *non-cooperative tax*.

Case (ii) *Only Environmental R&D:* $Z_r = 1, \quad Z_t = 0$

Again we have to consider various situations:

A) $\gamma_1 = 0$

Here we get

$$t - D' = \frac{R_2 \eta_2 c_t}{e' y} + \theta D' \tag{28}$$

which, when we compare the result with (22) tells us that if spillovers are zero then the *cooperative* and *non-cooperative* taxes are equal. Otherwise, the *cooperative* tax exceeds the *non-cooperative* tax rate.

This is just the result proved in Ulph (1994). We record it as

Result 11 When there is no process R&D, and when $k = 0$, then if there are environmental spillovers the *cooperative tax* exceeds the *non-cooperative tax*, otherwise the two are equal.

B) & C) $\gamma_1 \neq 0$

Now (27) becomes

$$(t - D')\left[(-\bar{\xi}\, e) + (-e' y)\frac{r'}{\gamma_1}\right] = \left[R_2 - \theta e D'\right].\bar{\xi} - (R_2 \eta_2 c_t)\frac{r'}{\gamma_1} - \theta y D' e' \frac{r'}{\gamma_1} \tag{29}$$

Assuming the coefficient on $(t - D')$ is positive then its sign depends on the sign of the RHS of (29). The *rival output effect* is positive. However the remaining two effects are pulling in different directions, since clearly if an increase in the common tax rate stimulates greater R&D this is harmful from the point of view of the *strategic over investment effect*, but beneficial from the point of view of the *spillover via investment effect*. So the overall sign of these last two effects will depend on

(i) which of the two effects is dominant;

(ii) the sign of $\frac{r'}{\gamma_1}$

So again there is little that can be said about whether the *cooperative* tax is above or below either marginal damage or the *noncooperative* tax.

Finally we turn to

Case (iii) *Both Environmental R&D and Process R&D:* $0 < Z_e < 1, \quad Z_t > 0$

In situation

A) $\gamma_1 = 0$

Then (27) becomes

$$t - D' = \frac{R_2\eta_2 c_t}{e'y} \frac{r'}{Z_r r' + Z_t} + \theta D' \qquad (30)$$

Notice that in this case $\rho_2 = 0$, so $r' = \rho_1$, so if we substitute this into (30) and compare it with (25) then we see that we can have the following

Result 12. When there is both environmental and process R&D, then, when $k = 0$, if environmental spillovers are positive the *cooperative* tax exceeds the *non-cooperative* tax, otherwise the two are equal.

So once agaian the broad qualitative results we obtain when there is both environmental and process R&D are exactly the same as obtained in Ulph (1994) for the case in which there is only environmental R&D.

Finally in situations

B) & C) $\gamma_1 \neq 0$

(27) becomes

$$\begin{aligned}(t - D')\left[\left(-\bar{\xi}\, e\right) + \left(-e'y\right)\frac{Z_r r' + Z_t}{\gamma_1}\right] = \\ \left[R_2 - \theta e D'\right].\bar{\xi} - \left(R_2\eta_2 c_t\right).\frac{r'}{\gamma_1} - \theta y D' e'.\frac{Z_r r' + Z_t}{\gamma_1}\end{aligned} \qquad (31)$$

There is not much that can be said here. If $r' > 0$ and so $Z_r r' + Z_t > 0$ then the *strategic over investment effect* and the *spillover via investment effect* again pull in opposite directions, but it is difficult to say much more. If $r' < 0$, but $Z_r r' + Z_t > 0$, and $\gamma_1 > 0$ then all three terms on the RHS of (31) are positive so assuming the coefficient on $(t - D')$ is positive,the *cooperative tax* exceeds marginal damage.

Beyond this, however, there are no general results to be otained.

Section 4. Using Standards as Instruments

In this section we analyse the use of standards as a policy instrument. It will turn out to be more useful to make a change of variable. Thus define $h_i \equiv \frac{1}{e_i}$, $i = 1,2$ as the *output-emissions* ratio, and $\equiv(h)$ as the cost of the R&D required to achieve output-emission ratio h, where it is assumed that $\equiv$ is increasing and strictly convex.

<u>Stage 3 Game - Market Output.</u>

Let E_i denote the emission standard set by government i. i.e. the maximum level of emissions that the firm in country i is permitted to emit. Then firm 1 takes as given E_1, x_1, h_1 *and* y_2 and chooses y_1 to maximise:

$$R(y_1, y_2) - a(x_1).y_1 \qquad s.t. \qquad y_1 \leq E_1.h_1$$

for which the first-order condition is simply:

$$R_1 - a \;\; \geq \;\; 0; \qquad y_1 \;\; \leq E_1.h_1$$

where the two inequalities hold with complementary slackness.

In other words, either the firm is on its Cournot reaction function, in which case the emission standard does not bite and marginal profits are zero, or else the emission standard bites, in which case marginal profits are positive. For reasons we shall give shortly, we shall assume that the equilibrium of this stage involves the emission standards for both firm biting.

<u>Stage 2 Game - R&D Investment.</u>

Firm 1 takes as given E_1 *and* y_2 and chooses x_1 *and* h_1 to maximise:

$$R(E_1.h_1, y_2) - a(x_1).E_1.h_1 - x_1 - \phi(h_1)$$

for which the first-order conditions are:

$$-a'(x_1).E_1.h_1 - 1 = 0 \qquad (32)$$

$$(R_1 - a)E_1 - \phi'(h_1) \leq 0 \qquad h_1 \geq 0 \qquad (33)$$

Now from (33) it is clear that if the emission standard constraint does not bite then, by the first-order condition for the Stage 3 game, firm 1 will invest nothing in environmental

R&D. This makes sense, since in the standards model environmental R&D plays no role in reducing costs of production, and hence affecting profits or market share; its sole role is to allow the firm to produce more output without violating the emission standard; but if that constraint is not binding, then the firm would not incur the costs of doing environmental R&D. What this would imply is that the government has set emission standards such that, even with no environmental R&D the firm is able to produce its profit-maximising output level without violating the emission standard. So the emission standard is placing no constraint on the firm's activities. For this model to have any interest, then, it is reasonable to assume that the emission standards must be playing a role, in which case they must bite in Stage 3.

It is important to note that in (32) and (33) there is no *strategic element* i.e. the firm is not using its R&D decisions to try to influence the output of its rival in the stage 3 output game. The reason is obvious; by taking as given the environmental R&D level and emission standard of its rival, the firm is taking as given the output of its rival, so the firm does not believe it can influence what its rival will produce.

We can solve (32) and (33) to get:

$$h_1 = F(E_1, y_2) \qquad (34a)$$

$$x_1 = G(E_1, y_2) \qquad (34b)$$

It is straightforward, if tedious, to show that $F_y, G_y < 0 \quad but \quad F_E, G_E$ cannot be signed. The rationale is as in the case of taxes: increasing rival output reduces the profitability of doing R&D; increasing emission standards will increase output, for any given R&D level, lowering the profitability of R&D, but it will also increase the effectiveness of R&D, in the sense that the increase in output for a given increase in the emissions-output ratio will be greater. Thus it is not possible to predict the effect of a slackening of environmental policy on the domestic firm's R&D.

To solve for an equilibrium of the Stage 2 game we write (34a) as:

$$h_1 = F\{E_1, E_2, F(E_2, E_1, h_1)\} \equiv H(E_1, E_2)$$

$$where \quad H_1 = \frac{\partial h_1}{\partial E_1} = \frac{[F_E + (F_y)^2 y]}{[1-(E.F_y)^2]}$$

$$H_2 = \frac{\partial h_1}{\partial E_2} = \frac{F_y.[F + E.F_E]}{[1-(E.F_y)^2]}$$

$$and \qquad 1-(E.F_y)^2 > 0$$

Now note that because of the ambiguous effect of an increase in emissions standards on own firm's emissions/output ratio the signs of both derivatives of H are also ambiguous. However if relaxing environmental policy (raising emission standards) increases domestic firm's emissions/output ratio, (i.e. $F_E > 0$) holding constant other firm's output, then that will also raise domestic firm's *equilibrium* emissions/output ratio, and lower rival's emissions/output ratio. Even if $F_E < 0$ this could still be the effect of raising emissions standards, so it will require an increase in emissions standards to have a marked negative effect on domestic emissions/output ratio before the predictions above are reversed.

We can now solve for equilibrium levels of process R&D by writing:

$$x_1 = G[E_1, E_2 . H(E_1, E_2)] \equiv J(E_1, E_2)$$

For the same reasons as above it is not possible to unambiguously sign the derivatives of J(.,.).

Stage 1 Game - Setting Emission Standards

(a) Non-Co-operative Governments.

The government in country 1 takes as given E_2 and chooses E_1 to maximise:

$$W = R(y_1, y_2) - a(x_1)y_1 - x_1 - \phi(h_1) - D(E_1 + \theta E_2)$$

$$where \quad y_1 = E_1 . H(E_1, E_2), \quad y_2 = E_2 . H(E_2, E_1) \quad and \quad x_1 = J(E_1, E_2)$$

The first-order condition is:

$$\frac{\partial W}{\partial E_1} = [R_1 - a].h_1 + [(R_1 - a) - \phi'].H_1 - [y_1 a' + 1].J_1 + R_2 . E_2 . H_2 - D' \qquad (35)$$

From (32) and (33) the second and third terms of (35) are zero so the first-order condition for setting emission standards can be written as:

$$D' = (R_1 - a).h_1 + R_2 . E_2 . H_2 \qquad (36)$$

The left-hand side is the marginal damage cost of higher emissions; the right-hand side is the marginal benefit of higher emissions; the first term is just the marginal profit of the extra output firm 1 will produce when emission standards of government 1 are increased; the second term is the *strategic incentive* for the government of country 1 to distort its environmental policy. From the above discussion, it is not possible to sign this second term, so environmental policies may be either laxer or tougher than first-best. But, for a wide range of cases the prediction would be that a relaxation of environmental standards by government 1 will cause the rival firm to cut its equilibrium environmental R&D and hence lower its equilibrium emissions/output ratio. In that case the second term on the RHS will be positive, so environmental policy will be laxer than first-best. Note that it is rather easier to reach such a judgement in the case of standards than taxes. The reason is that there are fewer strategic effects of environmental policy than in the case of taxes, since there are no direct incentives for either firms or governments to manipulate the market game; the only scope for the government to influence the stage 3 output of the rival firm, is by influencing the environmental R&D of the rival firm; if by raising the emission standards faced by its domestic firm the government reduces the incentives for the rival producer to do environmental R&D then the government will relax its environmental policy.

(B) Co-operative Governments.

As in the tax section, given our assumption of symmetry, we model co-operative governments by setting $E_1 = E_2 = E$ and choosing E to maximise the welfare of a single country. The first-order condition is:

$$\frac{\partial W}{\partial E} = [R_1 - a]h_1 - (1+\theta)D' + [(R_1 - a)E_1 - \phi'].\frac{dh_1}{dE} - [ya' + 1].\frac{dx_1}{dE} + R_2.[h_2 + E_2\frac{dh_2}{dE}] = 0$$

Using (32) and (33) we can re-write this as:

$$D' = \frac{\{[R_1 - a]h_1 + R_2 E_2 \frac{\partial h_2}{\partial E_1}\} + R_2[h_2 + E_2 \frac{\partial h_2}{\partial E_2}]}{(1+\theta)} \qquad (41)$$

Now the first term in the numerator of (41) is the same as the RHS of (40), so (41) tells us that there are three reasons why the co-operative level of emission standards will differ from the non-co-operative level of emission standards.

The first, is captured by the second term in the numerator of (41). The term in square brackets here is just the total effect on output in country 2 of a slackening of its emissions standards (an increase in E_2). If this is positive, then, given that $R_2 < 0$ this term is negative which means that countries would go for a lower level of marginal damage (tougher standards) than they would do in the non-cooperative equilibrium. If, however, we have an extreme form of the Porter hypothesis whereby a slackening of standards in country 2 so reduces the level of R&D in country 2 that output there actually falls, then this first factor would lead to laxer environmental standards than would prevail in the non-cooperative equilibrium.

The second effect is reflected in the denominator of (41) and captures the spillover effect of transboundary pollution. This has the effect of requiring lower marginal damages, and hence lower (tougher) emission standards; this is he standard effect of co-operation in the face of transboundary pollution.

Conclusions

In this paper we have undertaken a general analysis of the strategic setting of environmental policies when firms are also acting strategically within a *non-tournament* model of R&D competition. The analysis has enabled us to see how existing results in the literature emerge as special cases, and are indeed special. In particular, in the case where there is only process R&D Ulph (1993a) showed that if governments relax their environmental policies, this would unambiguously increase the domestic firm's R&D and reduce the rival's R&D, and, combined with the usual rent-shifting argument for relaxing R&D governments would unambiguously be led to relax their environmental policies. In Ulph (1994) it was shown that if there is only environmental R&D, then, in the case of emission taxes, it was now ambiguous whether relaxing environmental policy would encourage or discourage domestic R&D and this meant that it was also ambiguous whether governments would want to set too lax or too tough environmental policies. It might have been thought that when both forms of R&D were introduced this would leave the overall direction of distortion of R&D ambiguous, but imply that there would be a wider range of cases for which the distortion would take the form of relaxing environmental policy. This turns out not to be the case. The class of cases for which environmental policy will be too lax or too tough will be exactly the same as in the case where there is only environmental R&D. The rationale is that if nature of the environmental R&D function is such that firms do the amount of environmental R&D that will exactly offset the effect of an emissions tax, then the tax can have no effect on the amount of process R&D that firms would carry out; if the nature of the environmental R&D function is such that an increase in emission tax would cause the domestic firm's costs to rise, that would be an argument for relaxing environmental policy; but the higher costs will also discourage process R&D so that just reinforces the argument for relaxing environmental taxes; finally if the nature of the environmental R&D function is such that an increase in emissions tax would cause domestic firm's costs to fall, that will be an argument for toughening environmental policy; but the fall in costs will also induce the domestic firm to do more process R&D, reinforcing the fall in costs, and reinforcing the case for toughening emission taxes. Thus process R&D merely reinforces what is happening as a result of environmental R&D. Of course the possibility of doing process R&D will change the quantitative amount by which environmental policy gets distorted, but it does not affect the direction of the distortion. Thus in the case of emission taxes the general model shows that the results in Ulph (1994) are what drive the distortion in emission tax policy, and the model of Ulph (1993), considering only process R&D is a very special case. In confirming that the results of Ulph (1994) are the key driving results, our general model also confirms the finding of that paper that the model of Bradford and Simpson, with the exponential environmental R&D function, is also a very special model.

The above argument was couched in terms of emission taxes. With emission standards, which were not analysed in Ulph (1994), the argument is broadly the same as for taxes, though for somewhat different reasons. In out model, where direct abatement plays no role, the use of emission standards rules out any strategic role for process R&D, and so it can only be environmental R&D which determines the direction of distortion of environmental policy.

It should be noted that our model has omitted domestic consumers, unlike the papers of Kennedy (1993) or Conrad (1993). As those papers show, including domestic consumers is likely to reinforce any tendency of environmental policy to be relaxed, since the government wishes to expand output which is being kept its first-best level by imperfect competition, so the extension of the model in that direction is unlikely to add very much.

In terms of future research, the most pressing need is for empirical work based on models of imperfect competition to establish whether the biases in environmental policy identified by the theoretical analysis of the literature to which this paper contributes are likely to be of any quantitative significance.

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