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Market Structure and Environmental Innovation.

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Abstract

This paper studies firms' incentives to invest in environmental R&D under different market structures (Cournot and Bertrand) and environmental policy instruments (emission standards, taxes, tradeable permits and auctioned permits). Because of market strategic effects, R&D incentives vary widely across market structures and instruments. For example, when firms' products are strategic substitutes (i.e., Cournot), either emission standards, taxes or auctioned permits can provide the most incentives. But when firms' products are strategic complements, either taxes or auctioned permits provide the most incentives. If markets are perfectly competitive, however, permits and emission standards offer similar incentives that

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are lower than those offered by taxes (*JEL:* L13, L50, Q28; key words: environment, regulation, market structure, innovation)

1 Introduction

The relationship between market structure and technical progress has attracted significant attention from economists over the last decades. Motivated by the notion that technical progress is perhaps the main vehicle to solve environmental problems in the long-run (Kneese and Schultze, 1978), economists have also focused on the extent to which different environmental policy instruments provide firms with incentives to invest in environmental R&D.[1] This latter work has been carried out under the assumption of perfect competition, abstracting from market structure considerations (Tietenberg, 1985; Milliman and Prince, 1989; Jung et al., 1996; Requate, 1998; and Parry, 1999).[2] In general, authors have found that market-based regulatory instruments such as taxes, tradeable permits and auctioned permits provide more R&D incentives than command-and-control instruments such as emission standards.[3]

In this paper, I extend the study of firms' incentives to invest in environmental R&D by considering the possibility of imperfect competition in output and permit markets. Since real-world markets are rarely perfectly competitive, extending the environmental

[1] See, for example, Hahn and Stavins (1992), and Newell et al. (1999) for very recent empirical work.

[2] One exception is Biglaiser and Horotiwz (1995) that consider firms interaction in the market for the discovery of new pollution-control technologies and assume perfect competition in the output market. While they focus on the optimal design of a technology standard coupled with a tax, in this paper I focus on the comparison among individual instruments.

[3] Less consistent with the above findings are the works of Magat (1978) and Malueg (1989), who showed that relative incentives may vary depending on firm's specific technologies and elements of instrument design. Laffont and Tirole (1996) have also shown that plain tradeable permits may offer little R&D incentives, but the introduction of advance permits and options can restore these incentives. However, they did not compare permits with other instruments.

innovation literature to allow for imperfect competition can have important policy implications. In fact, the industrial organization literature has shown that strategic or market interactions in oligopoly markets can significantly affect “investment decisions”, including cost-reducing R&D (Brander and Spencer, 1983; Spence, 1984; Fudenberg and Tirole, 1984; and Bulow et al., 1985).[4] Depending on the market structure, some firms may have incentives to overinvest while others may have incentives to underinvest. While it is likely that these strategic interactions also affect firms' incentives to invest in environmental R&D, it remains to be seen whether the changes in incentives significantly affect the “environmental R&D rankings” found by previous studies. It may well be that incentives under market-based instruments are still greater (although different in magnitude from the earlier findings) than they are under command-and-control instruments.

To study the effect of imperfect competition on environmental R&D, I extend the model of Montero (2002) and have two firms (1 and 2) competing in either quantities (i.e., Cournot competition) or prices (i.e., Bertrand competition) in the output market and at the same time being subject to an environmental regulation. The regulatory goal is to limit emissions at some predetermined level by means of one of the following four regulatory instruments: emission standards, taxes, (grandfathered) tradeable permits and auctioned permits. Firms can reduce their compliance costs and improve their position in the output market by investing in environmental R&D.

As explained by Tirole (1988, pp. 323-336), in such a market-regulatory setting, firm 1's incentive to invest in R&D results from two effects. The *direct* or *cost-minimizing*

[4] For a complete survey on strategic interaction in oligopoly markets, see Shapiro (1989) and Tirole (1988).

effect accounts for that fraction of firm 1's cost savings (or profit increase) that does not affect firm 2's choice of output. In other words, this effect would exist even if firm 1's R&D investment were not observed by firm 2 before the latter determined its output. The *strategic effect*, on the other hand, results from the influence of firm 1's R&D investment on firm 2's choice of output. For example, firm 2 may increase its output as an optimal response to firm 1's R&D investment adversely affecting firm 1's profits. Hence, it may be optimal for firm 1 to invest less in R&D in order to avoid an aggressive response by firm 2 in the output market. The sign of this strategic effect may be positive or negative depending on the market-regulatory structure. Not surprisingly, after accounting for direct and strategic effects, the results of this paper indicate that the "R&D rankings" of instruments differ in many ways from earlier findings. In fact, I find situations in which standards offer greater R&D incentives than the other three instruments.

The rest of the paper proceeds as follows. In Section 2, I develop the basic model and explain how to estimate firms' incentives to invest in environmental R&D. In Section 3, I assume that firms compete à la Cournot in the output market and estimate R&D incentives under the four aforementioned regulatory instruments. In Section 4, I repeat the analysis of Section 3 but now assuming that firms compete à la Bertrand. In Section 5, I develop some numerical examples to illustrate and complement some of the analytical results of the previous sections using the social optimum solution as a benchmark. In Section 6, I discuss R&D under perfect competition and provide concluding remarks.

2 The Model

Consider 2 profit-maximizing firms (denoted by i and j) competing under different market and regulatory structures. When firms compete à la Cournot in the output market (i.e., firms' outputs are strategic substitutes), the inverse demand function is $P = P(Q)$, where P is the output market price and $Q = q_i + q_j$ is industry output. When firms compete á la Bertrand (i.e., firms' outputs are strategic complements), the demand curve faced by firm i is $q_i = D_i(p_i, p_j)$, where p_i is the price chosen by firm i.

Without loss of generality, firm i produces q_i at no cost, and in the absence of any regulation, production leads also to q_i units of emission. Emissions can be reduced at a total cost of $C(r_i)$, where r_i is the amount of emissions reduced, and, as usual, $C_i' > 0$ and $C_i'' > 0$. It is convenient to re-write the abatement function as $C_i(q_i - e_i)$, where $q_i - e_i \equiv r_i$ and e_i is firm i's emissions after abatement. Thus, if the firm does not abate any pollution $e_i = q_i$.

The environmental regulatory structure consists of a goal and instrument. I assume that the regulatory goal is to limit aggregate emissions at some level $\overline{E} = e_i + e_j$ by means of one of the following four regulatory instruments: emission standards, taxes, (grandfathered) tradeable permits and auctioned permits. Under emission standards, firms' emissions are limited to $\overline{e}_i$ and $\overline{e}_j$ respectively, such that $\overline{e}_i + \overline{e}_j = \overline{E}$. Under tax regulation, firms pay τ dollars for each unit of emissions. The tax level τ is set based on the production technology, output demand, and current abatement technology (i.e., before R&D) to yield $\overline{E}$. Under permits regulation, a total number of $\overline{E}$ permits are either distributed freely or auctioned off. I assume that each instrument design remains unchanged regardless the amount of R&D undertaken afterwards. Alternatively, one could assume that the regulator is unable to observe R&D investments or that observes them after a long time.

Firms engage in output competition taking into account R&D investments that can reduce their environmental compliance costs, and hence, their ability to compete in the market. Following Spence (1984), I assume that if firm i and firm j invest in environmental R&D, abatement costs reduce from $C_i(q_i - e_i)$ to $k_i C_i(q_i - e_i)$, where k_i is a R&D production function of the form[5]

$$k_i = f_i(K_i + \theta K_j) \tag{1}$$

where K_i is firm's i R&D effort with a total cost of $v_i K_i$,[6] $f(0) = 1$, $f(\infty) > 0$, $f' < 0$, $f'' > 0$, and $0 \leq \theta \leq 1$ is a parameter intended to capture possible spillovers. If $\theta = 0$ there are no spillovers, while if $\theta = 1$ the benefits of each firm's R&D efforts are fully shared.[7]

Depending on the regulatory instrument, the solution of the model involves either a two-period or three-period equilibrium. In the case of emission standards and taxes there are two periods. First, the two firms choose R&D levels K_i and K_j respectively, which

[5] This way of modeling innovation applies more naturally to production process innovation at the firm. For example, under Title IV of the 1990 Clean Air Act Amendements electric utilities have been making "R&D efforts" to retrofit their boilers to burn different type of coals and hence reduce their compliance costs.

[6] Although one could simply treat K_i as dollars invested in R&D, this formulation facilitates the numerical resolution of the model. Still, I will often use the words "R&D investment" to refer to K.

[7] Note that innovation process could also be modeled as a patent race where firms compite to discover a new technology k (< 1) that reduces abatement costs. This sort of race gives rise to the "common pool" effect where firms tend to overinvesment in R&D (Loury, 1979); something we do not have in this model but that should not change the qualitative results of the paper.

are known to both firms, and then, actions a_i and a_j (which can be either quantities or prices), and emission levels e_i and e_j are simultaneously determined. In the case of permits, there are three periods. First, the two firms choose R&D investments K_i and K_j, then, emission levels e_i and e_j (by the amount of permits withheld) and permits price σ are determined, and finally, actions a_i and a_j are resolved.[8]

To decide upon the amount of R&D to undertake, firms must have some expectation about how the permits and output markets' equilibria will be resolved. I assume, that for any given level of R&D, firms have complete information, and therefore, correctly anticipate the Nash equilibrium afterwards, which is resolved either as a Cournot game or as a Bertrand game with differentiated products. When the environmental regulation takes the form of tradeable or auctioned permits, I assume that for any given level of R&D and expected output, firms Nash bargain over the permits price σ (total quantity is fixed at $\overline{E}$). Since information is complete and there are no income effects, the Nash bargaining solution leads to the efficient level of emissions for any given level of investment (K_i and K_j) and expected actions (a_i and a_j), regardless the initial distribution of the tradeable permits (Spulber, 1989).

The optimal amount of R&D to undertake by firm i under different market and regulatory structures could be obtained from maximizing $\pi_i(K_i, K_j) - vK_i$, where $\pi_i(K_i, K_j)$ represents firm i's profits resulting from the subgame perfect Nash equilibrium in the permits (if it is the case) and output markets after observing R&D levels K_i and K_j. The solution K_i^* must satisfy $d\pi_i(K_i, K_j)/dK_i = v_i$, where $d\pi_i(K_i, K_j)/dK_i$ is the total

[8]Since permits can be considered as another input into the production process, it is natural to think that the permits market clears before the output market.

derivative of π_i with respect to K_i.

Rather than estimating K_i^* directly, however, in this paper I compare R&D incentives from the total derivative of $\pi_i(k_i, k_j)$ with respect to k_i, that is $d\pi_i/dk_i$. Because K_i^* solves

$$\frac{d\pi_i}{dK_i} = \frac{d\pi_i}{dk_i} f'(K_i + \theta K_j) = v_i \tag{2}$$

and $f' < 0$, and $f'' > 0$, it is immediate that K^* increases with $-d\pi_i/dk_i$, regardless the level of spillovers θ.[9] Thus, if $-d\pi_i^A/dk_i$ and $-d\pi_i^B/dk_i$ are the total derivatives corresponding to regulatory instruments A and B, respectively, we would have that A leads to greater R&D than B does if $-d\pi_i^A/dk_i > -d\pi_i^B/dk_i$ for all k_i. If $-d\pi_i^A/dk_i > -d\pi_i^B/dk_i$ for only some values of k_i, however, we would have that instrument A may lead to more, equal or less R&D than instrument B depending on the value of market, regulatory, and R&D parameters. In this situation, for example, one instrument can more effectively force drastic innovations (big reductions in k) than the other instrument.

3 R&D under Cournot competition

In this section, I solve the model and estimate the value of $-d\pi_i/dk_i$ for each regulatory instrument when firms compete à la Cournot. I assume that firms are symmetric in all respects, including their allocation of emission standards and tradeable permits.

[9] Since $k = f((1+\theta)K)$, the FOC (2) can be entirely written as a function of k as $d\pi/dk = v/f'(f^{-1}(k))$, which solution k^* will be unique and independent of θ. Note, however, that K^* is a decreasing function of θ.

3.1 Emission Standards

Under emission standards regulation and Cournot competition, for any given a level of k_i and k_j (or K_i and K_j), firm i maximizes profits

$$\pi_i(k_i, k_j) = P(Q)q_i - k_i C_i(q_i - e_i) \tag{3}$$

subject to $e_i \leq \overline{e}_i$, where $\overline{e}_i$ is the emission standard established for firm i and $Q = q_i + q_j$. Setting $e_i = \overline{e}_i$, the second-period equilibrium is given by the following first-order condition (FOC) for q_i

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - \overline{e}_i) = 0 \tag{4}$$

The third term of (4) indicates that the environmental regulation rises marginal production costs by an amount equal to marginal abatement cost at $e_i = \overline{e}_i$, which depends on the amount of R&D undertaken.

The incentives to invest in R&D are obtained from the (negative) value of the total derivative of (3) with respect to k_i at the optimum level of output and emissions. Using the envelope theorem, this derivative is equal to

$$-\frac{d\pi_i}{dk_i} = C_i(q_i - \overline{e}_i) - P'(Q)q_i \frac{dq_j}{dk_i} \tag{5}$$

The first term on the right-hand side (RHS) of (5) is the direct effect, which is always positive and increasing with the amount of abatement $q_i - e_i$. Hence, the tighter the standard (i.e., the lower $\overline{e}$ becomes) the higher the direct incentives.

The second term on the RHS of (5) is the strategic effect. This effect results from the influence of R&D investment on firm j's second period action. Since $P' < 0$, its sign depends on the sign of dq_j/dk_i. In this emission-standards-Cournot game, environmental R&D can be interpreted as pure cost-reducing innovation, and therefore we should expect that $dq_j/dk_i > 0$. The implication is that a lower k_i, which means lower marginal abatement costs $k_i C_i'$, raises firm j's relative costs reducing its output. This interaction in the output market results in a positive strategic effect, leading to more R&D than otherwise.

Obtaining an expression for dq_j/dk_i (see Appendix A), eq. (5) becomes

$$-\frac{d\pi}{dk} = C(q - \overline{e}) - P'q \frac{C' \cdot (P' + P''q)}{(kC'' - P')(3P' + 2P''q - kC'')} \tag{6}$$

Assuming that $P' + P''q < 0$ to insure the existence of a unique pure-strategy Nash equilibrium in output (Gaudet and Salant, 1991), the fraction dq_j/dk_i of the second term in (6) is indeed positive and so is the strategic effect.[10] Using Fudenberg and Tirole's (1984) taxonomy, under these market and regulatory structures where products are strategic substitutes, firm's optimal strategy is to behave as a "top dog" and overinvest in R&D.[11]

[10]Note that the second term becomes also positive for a linear demand curve.

[11]Note that we are in a case of accomodation of entry rather than entry deterrence.

3.2 Taxes

Under tax regulation and Cournot competition, for any given a level of k_i and k_j, firm i maximizes profits

$$\pi_i(k_i, k_j) = P(Q)q_i - k_i C_i(q_i - e_i) - \tau e_i \tag{7}$$

where τ is a fixed tax that firm i must pay for each unit of emission. The second-period equilibrium is given by the FOCs for e_i and q_i

$$k_i C_i'(q_i - e_i) - \tau = 0 \tag{8}$$

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - e_i) = P(Q) + P'(Q)q_i - \tau = 0 \tag{9}$$

Equation (8) indicates that at the optimum, marginal abatement costs are equal to the tax level τ, which implies that the oligopoly structure of the industry does not affect the cost-effectiveness property of taxes. Eq. (9) shows that the environmental regulation rises the marginal cost of production by τ, which is independent of the amount of R&D. The latter is because the firm simultaneously adjusts q_i and e_i for (8) to always hold.

According to (9) then the optimal q_i is independent of k_i and k_j, which in turn implies that q_j will be independent of k_i and k_j as well. The reason is that the marginal cost of production (which here reduces to environmental compliance only) for both firms is constant at τ.[12] Therefore, $dq_j/dk_i = 0$ and the (negative) value of the total derivative

[12]Note that if we let the production cost be cq the total marginal production cost will still be constant

of (7) with respect to k_i at the optimum is, from the envelope theorem, equal to

$$-\frac{d\pi}{dk} = C(q - e) \tag{10}$$

Under tax regulation there is no strategic effect because firm i's R&D investments do not affect its marginal production costs (they do affect total costs), and consequently, its output.

Let us now compare incentives under taxes and under emission standards. Equation (10) differs from (6) in some important ways. First, before any investment in R&D is undertaken (i.e., $k_i = 1$), (4) and (9) indicate that output levels are the same by regulatory design (tax level τ leads to emissions $\overline{e}_i$ before R&D). This implies that the direct effect $C_i(q_i - e_i)$ is the same for both emission standards and taxes. However, under emission standards regulation there is a positive strategic effect that increases R&D incentives, which is measured by the second term of (6). Thus, if the R&D function $f(\cdot)$ is such that only mild innovations take place (optimal k close to 1), R&D is likely to be higher under emission standards.

Second, at positive levels of R&D (i.e., $k_i < 1$), the direct effect is greater under taxes because the corresponding abatement level is larger. Re-writing the output FOCs

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - \overline{e}_i) \tag{11}$$

and equal to $c + \tau$.

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - e_i) = \tau \tag{12}$$

we can observe that under tax regulation q_i is independent of k_i, while under emission standards q_i must increase if k_i drops for eq. (11) to continue holding given that $\overline{e}_i$ is fixed and $P' + P''q < 0$ by assumption (to insure the existence of a unique pure-strategy Nash equilibrium in output). From the latter, we also have that an increase in q_i reduces the LHS of (11) below the LHS of (12). This implies that the amount of abatement under emission standards, $q_i - \overline{e}_i$, is lower than under taxes and so is the direct effect.

The importance of the strategic effect of emission standards relative to the direct effect of either taxes or standards depends on the demand curve $P(Q)$ and the emissions goal $\overline{E}$. To see this in a very simple way, consider the following change to the market-regulatory situation: a positive parallel shift of a linear demand curve from P to αP ($\alpha > 1$), with $P' < 0$ and $P'' = 0$ unchanged, and the same tax level τ, which necessarily implies a higher emissions goal $\overline{E}$ and emission standards $\overline{e}_i$. Under tax regulation, this new situation leads to higher output q_i (see (9)), same abatement $q_i - e_i$ (see eq. (8)), and hence, higher emissions. Now, the direct effect of either instrument at any k_i remains unchanged because the optimal amount of abatement is not affected by α.[13] And from (6) and $P'' = 0$, we can see that the strategic effect increases with q. Thus, by increasing α (and adjusting $\overline{E}$ accordingly) we can let the strategic effect of emission standards to

[13] In the case of taxes is immediate since τ has not changed. In the case of emission standards note, first, that abatement $q_i - \overline{e}_i$ at $k = 1$ is independent of α and, from (4), that

$$\frac{dq_i}{dk_i} = \frac{-C_i'}{2P' + P'' - k_i C_i''}$$

is indepent of α.

be as large as we like without affecting the direct effect under either instrument. We can summarize the comparison between taxes and emission standards in the following proposition.

Proposition 1 *Under Cournot competition in the output market, taxes can provide more, less, or the same R&D incentives than emission standards.*

The R&D ranking between taxes and emission standards will ultimately depend on the relative importance of the regulatory goal, output demand and R&D production function $f(\cdot)$. Emission standards are likely to offer greater R&D incentives when the $f(\cdot)$ and v are such that only minor innovations take place, and when output demand is large and/or more inelastic for the strategic effects to be more important. On the other hand, taxes are likely to provide more incentives at stricter regulatory levels (higher τ and lower $\overline{e}$) because direct effects become relatively more important. We shall illustrate these results with the aid of numerical examples.

3.3 Permits

Because grandfathered tradeable permits and auctioned permits are very closely related, I shall merge their analysis into one but emphasizing their differences as they arise. Thus, under "permits" regulation and Cournot competition, for any given level of k_i and k_j, firm i maximizes profits

$$\pi_i(k_i, k_j) = P(Q)q_i - k_i C_i(q_i - e_i) - \sigma \cdot (e_i - \epsilon_i) \tag{13}$$

where ϵ_i is amount of (tradeable) permits received by firm i and σ is the market clearing price of permits after a total of $\overline{E}$ permits are distributed gratis by the regulator. If instead, the $\overline{E}$ permits are auctioned off, $\epsilon_i = 0$ and both firms become buyers of permits. The auction clearing price is the same as in the permits market because there are no income effects.

Since the permits market (or auction market) operates first, we start by solving the third-period output equilibrium. Firm i takes e_i as given, which is the number of permits withheld in the second period, and maximizes $P(Q)q_i - k_i C_i(q_i - e_i)$. The FOC is

$$P(Q) + P' q_i - k_i C_i'(q_i - e_i) = 0 \tag{14}$$

Letting $\widehat{q}_i(e_i)$ be the solution to the third-period output equilibrium, in the second period firm i chooses e_i to maximize $P(Q)\widehat{q}_i(e_i) - k_i C_i(\widehat{q}_i(e_i) - e_i) - \sigma \cdot (e_i - \epsilon_i)$. Using the envelope theorem, the Nash bargaining equilibrium in the permits market is given by (Spulber, 1989)[14]

$$k_i C_i'(\widehat{q}_i(e_i) - e_i) = k_j C_j'(\widehat{q}_j(e_j) - e_j) = \sigma \tag{15}$$

$$e_i + e_j = \overline{E} \tag{16}$$

Thus, the (negative) value of the total derivative of (13) with respect to k_i at the

[14]Firms bargain over σ until no further exchange of permits is mutually beneficial while taking into account their correct expectation of future outputs $\widehat{q}_i$ and $\widehat{q}_j$.

subgame perfect Nash equilibrium in the permits and output markets is

$$-\frac{d\pi_i}{dk_i} = C_i(q_i - e_i) - P' q_i \frac{dq_j}{dk_i} + \frac{d\sigma}{dk_i}(e_i - \epsilon_i) \tag{17}$$

The first term on the RHS of (17) is the direct effect, the second term is the strategic effect from the output market and the third term is the strategic effect from the permits market. While the sign of the direct effect is clearly positive, the sign of other two effects is not so immediate.

In a permits-Cournot game, environmental R&D cannot readily be interpreted as pure cost-reducing innovation because there is an interaction in the permits market. Hence, dq_j/dk_i may no longer be positive as it was under standards. In fact, we have that (see Appendix B)

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - kC'')} \tag{18}$$

which is negative, since $P' + P''q < 0$ by assumption. The implication is that a lower k_i, which means lower marginal abatement costs $k_i C_i'$, reduces firm j's relative costs, increasing its output. The explanation is that any R&D investment made by firm i "spills over" through the permits market, lowering the price σ and consequently reducing abatement costs for both firms in the same amount at the margin, which ultimately helps firm j to increase output.

Investments in R&D also affect the permits market. As formally demonstrated in Appendix B, the total effect of R&D on the permits price is negative (i.e., $d\sigma/dk_i > 0$), regardless of who invest in R&D; otherwise firms' production would be lower after R&D since marginal production costs are equal to σ (see (14)). The sign of this strategic effect from the permits market depends on whether the firm i is a seller or buyer of permits. If the firm is a buyer of permits ($e_i > \epsilon_i$), this effect is positive because the firm now buys permits at a lower price.

Thus, the total derivative (17) becomes

$$-\frac{d\pi}{dk} = C(q-e) - \frac{P'C'q - C' \cdot (3P' + 2P''q)(e-\epsilon)}{2(3P' + 2P''q - kC'')} \tag{19}$$

While the strategic effect from the output market is always negative for either tradeable permits or auctioned permits, the strategic effect from the permits market is zero under tradeable permits ($e = \epsilon$) and positive under auctioned permits ($\epsilon = 0$). Therefore, we can establish the following proposition:

Proposition 2 *Under Cournot competition in the output market and imperfect competition in the permits market, a buyer of permits has greater R&D incentives than a seller of permits, and consequently, auctioned permits lead to more R&D than grandfathered permits.*

In terms of the Fudenberg and Tirole's (1984) taxonomy, eq. (19) indicates that when products are strategic substitutes and firms are under tradeable permits regulation, it is optimal to follow a "lean and hungry look" strategy and underinvest in R&D. If firms are under auctioned permits regulation, it may be optimal to follow a "top dog" strategy and overinvest in R&D.

The comparison between tradeable permits and the other two regulatory instruments, emission standards and taxes, is rather straightforward. At any value of k, direct effects under tradeable permits and standards are the same and lower than direct effects under taxes (unless $k = 1$ in which case are equal). And since strategic effects under tradeable permits are always negative, it follows:

Proposition 3 *Under Cournot competition in the output market and imperfect competition in the permits market, tradeable permits offer less R&D incentives than either emission standards or taxes.*

The comparison between auctioned permits and emission standards and taxes is more involved. At any value of k, direct effects under auctioned permits and standards are the same and lower than direct effects under taxes (unless $k = 1$ in which case they are equal). On the other hand, strategic effects from the permits market can be large enough for total effects to be higher than total effects under standards and taxes, as we shall see in the numerical section. Thus, we can establish

Proposition 4 *Under Cournot competition in the output market and imperfect competition in the permits market, auctioned permits can offer more, less, or the same R&D incentives than either emission standards or taxes.*

Results so far are based on the assumption of firms engaged in quantity competition for the output market. As Fundenberg and Tirole (1984) and Tirole (1988) have already shown, the sign of the strategic effect may change as firms engage in price competition for the output market. As we shall see below, this does not necessarily mean that previous propositions simply revert under price competition. There are regulatory interactions that must be taken into account as well.

4 R&D under Bertrand competition

In this section, I repeat the previous analysis but assuming instead that firms compete à la Bertrand with differentiated products. The demand curve faced by firm i is $q_i \equiv D_i(p_i, p_j)$, where (i) $-\partial D_i/\partial p_i \geq \partial D_i/\partial p_j > 0$ and (ii) $\partial^2 D_i/\partial p_i \partial p_j > 0$. Because products are not necessarily homogenous (i) simply indicates that a firm's price change has an equal or larger effect on its own demand than on its rival's. On the other hand, (ii) says that a firm's price increase has a smaller effect on its own demand the larger the price of its rival. I also assume that $D_i(p_i, p_j)$ is not too convex in p_i; otherwise second order conditions (SOCs) do not hold. To avoid cluster I will sometimes use the following notation: $D_1' \equiv \partial D_i/\partial p_i$, $D_2' \equiv \partial D_i/\partial p_j$, $D_{11}'' \equiv \partial^2 D_i/\partial p_i \partial p_i$ and $D_{12}'' = D_{21}'' \equiv \partial^2 D_i/\partial p_i \partial p_j$ (the same notation applies if we interchange i by j). Note that even if products are homogenous, i.e., $-D_1' = D_2'$, the competitive outcome, i.e., $p = kC'$, is not obtained because the emissions cap $\overline{E}$ acts as a capacity constraint.[15]

4.1 Emission standards

Under emission standards regulation and Bertrand competition, for any given a level of k_i and k_j, firm i maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C_i(D_i(p_i, p_j) - \overline{e}_i) \tag{20}$$

[15] See Kreps and Scheinkman (1983).

The FOC for p_i is

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C_i' \frac{\partial D_i}{\partial p_i} = 0 \tag{21}$$

and the (negative) value of total derivative of (20) at the optimum level of prices is

$$-\frac{d\pi_i(k_i, k_j)}{dk_i} = C_i(D_i - e_i) - (p_i - k_i C_i') \frac{\partial D_i}{\partial p_j} \frac{dp_j}{dk_i} \tag{22}$$

Because $\partial D_i / \partial p_j > 0$ and $p_i > k_i C_i'$ (capacity constraints allow firm i to exercise some market power even if product are homogenous), the sign of the strategic effect depends on dp_j/dk_i (see Appendix C for its derivation). Plugging dp_j/dk_i (see Appendix C for its derivation) into (22) we obtain for symmetric firms

$$-\frac{d\pi}{dk} = C(q - \overline{e}) - (p - kC')D_2' \frac{BD_1'C'}{(B^2 - A^2)} \tag{23}$$

where $A = (2D_1' - k(D_1')^2 C'' + (p - kC')D_{11}'')$ and $B = (D_2' - kD_1'D_2'C'' + (p - kC')D_{12}'')$. SOCs for a local maximum require that $A < 0$ and $A^2 - B^2 > 0$ (see Appendix C), so, as in the Cournot game, $dp_j/dk_i > 0$. Thus, (23) indicates that in this market structure where products are strategic complements, firm's optimal strategy is to behave as a "puppy dog" and underinvest in R&D.

4.2 Taxes

Under tax regulation and Bertrand competition, for any given level of k_i and k_j, firm i maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C(D_i(p_i, p_j) - e_i) - \tau e_i \tag{24}$$

The FOCs for e_i and p_i are, respectively

$$k_i C_i' - \tau = 0 \tag{25}$$

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C_i' \frac{\partial D_i}{\partial p_i} = D_i + p_i \frac{\partial D_i}{\partial p_i} - \tau \frac{\partial D_i}{\partial p_i} = 0 \tag{26}$$

Expression (26) indicates that p_i and p_j are not affected by the choice of k_i and k_j, so the total derivative of (24) at the equilibrium is given by

$$-\frac{d\pi}{dk} = C(q - e) \tag{27}$$

As before, under tax regulation there is no strategic effect because firm i's R&D investments do not affect its marginal production costs, and consequently, its output.

Now, we can compare R&D incentives under taxes and emission standards, given by eqs. (27) and (23) respectively, when firms play a Bertrand game in the output market. Before any investment in R&D is undertaken (i.e., $k = 1$), (26) and (21) indicate that output levels are the same by regulatory design (τ leads to emissions $\overline{e}$). This implies that the direct effect $C(q-e)$ is the same for both emission standards and taxes. However, under emission standards regulation there is a negative strategic effect that reduces R&D incentives, which is measured by the second term of (23). Similarly, at positive levels of R&D (i.e., $k < 1$), the direct effect is greater under taxes because the corresponding abatement level is larger. Since strategic effects continue to be negative for emission standards, it immediately follows the next proposition.

Proposition 5 *Under Bertrand competition in the output market, taxes offer more R&D incentives than emission standards.*

4.3 Permits

As before, the analysis of grandfathered tradeable permits and auctioned permits are merged into one. Under permits regulation and Bertrand competition, for any given level of k_i and k_j, firm i maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C_i(D_i(p_i, p_j) - e_i) - \sigma \cdot (e_i - \epsilon_i) \tag{28}$$

where ϵ_i is amount of (tradeable) permits received by firm i and σ is the market clearing price of permits after a total of $\overline{E}$ permits are distributed gratis by the regulator. If instead, the $\overline{E}$ permits are auctioned off, $\epsilon_i = 0$ and both firms are buyers of permits. Again, the auction clearing price remains the same as in the permits market because there are no income effects.

Since the permits market (or auction market) operates first, we start by solving the third-period output equilibrium. Firm i takes e_i as given, which is the amount of permits withheld in the second-period, and maximizes $p_i D_i - k_i C_i$ with respect to p_i. The FOC is

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C_i' \frac{\partial D_i}{\partial p_i} = 0 \tag{29}$$

Letting $\widehat{p}_i \equiv \widehat{p}_i(e_i)$ be the solution to the third-period price equilibrium, in the second period firm i chooses e_i to maximize $\widehat{p}_i D_i(\widehat{p}_i, \widehat{p}_j) - k_i C_i(D_i(\widehat{p}_i, \widehat{p}_j) - e_i) - \sigma \cdot (e_i - \epsilon_i)$. Using the envelope theorem, the Nash bargaining equilibrium in the permits market is given by (Spulber, 1989)[16]

$$k_i C_i'(D_i(\widehat{p}_i, \widehat{p}_j) - e_i) = k_j C_j'(D_j(\widehat{p}_i, \widehat{p}_j) - e_j) = \sigma \tag{30}$$

$$e_i + e_j = \overline{E} \tag{31}$$

Thus, the (negative) value of the total derivative of (28) with respect to k_i at the subgame perfect Nash equilibrium in the permits and output market is

$$-\frac{d\pi_i}{dk_i} = C_i(D_i - e_i) - (p_i - k_i C_i') \frac{\partial D_i}{\partial p_j} \frac{dp_j}{dk_i} + \frac{d\sigma}{dk_i} \cdot (e_i - \epsilon_i) \tag{32}$$

where the second term of the RHS of (32) is the strategic effect from the output market, and the third term is the strategic effect from the permits market.

Since $p_i > k_i C_i'$ and $\partial D_i / \partial p_j > 0$, the sign of the strategic effect from the output

[16] Firms bargain over σ based on their correct expectation of future prices $\widehat{p}_i$ and $\widehat{p}_j$.

market depends on the sign of dp_j/dk_i, which is (see Appendix D)

$$\frac{dp_j}{dk_i} = \frac{D_1'C'}{2(A+B)} = \frac{dp_i}{dk_i} \tag{33}$$

where A and B are as in section 4.1. Since SOCs require that $A+B<0$ (see Appendix C), we also have that $dp_j/dk_i > 0$. In this permits-Bertrand game, firm i's R&D (i.e., lower k) leads firm j to reduce its action p_j, and hence increase its profits, not only because of output complementarity but also because any R&D investment "spills over" through the permits market reducing abatement costs for both firms in the same amount at the margin. Because of this latter effect, it is not difficult to show that dp_j/dk_i under permits is always greater than under emission standards. Formally, this is the case because $A+B<0$.

The sign of the strategic effect in the permits market depends on the sign of $d\sigma/dk_i$ and on whether the firm i is a seller or buyer of permits. Since $d\sigma/dk_i > 0$ (see Appendix D for its derivation),[17] when a firm is a buyer of permits ($e_i > \epsilon_i$), the strategic effect from the permits market is positive. Accounting for strategic effects in both permits and output markets, the total derivative (32) becomes

$$-\frac{d\pi}{dk} = C(q-e) - \frac{(p-kC')D_2'D_1'C'}{2(A+B)} + \frac{kC''(e-\epsilon)}{2}\left(\frac{(D_1'+D_2')D_1'C'}{A+B} + \frac{C'}{kC''}\right) \tag{34}$$

In terms of the Fudenberg and Tirole's (1984) taxonomy, eq. (34) indicates that when

[17] The value of $d\sigma/dk_i$ is unambiguously positive when either products are homogeneous (i.e., $D_1'+D_2'=0$) or the demand curve is linear (i.e., $D_{11}'=D_{12}'=0$). If products are too differentiated (i.e., $D_1'+D_2' \ll 0$) and the demand curve is very convex (i.e., $D_{11}'' \gg 0$), $d\sigma/dk_i$ may become negative. However, we do not discuss this possibility further here in the interest of a fair comparison with the Cournot competition that is for homogenous products.

products are strategic complements, under tradeable permits regulation (i.e., $e = \epsilon$) it is optimal for a firm to follow a "puppy dog" strategy and underinvest in R&D. Under auctioned permits regulation (i.e., $\epsilon = 0$), on the other hand, it may be optimal for a firm to follow a "fat cat" strategy and overinvest in R&D.

We now can proceed to compare permits with emission standards and taxes. Comparing R&D incentives under tradeable permits ($e = \epsilon$) and emission standards only requires to compare dp_j/dk_i since direct effects are the same for both instruments at any value of k. Consequently, we have the following proposition

Proposition 6 *Under Bertrand competition in the output market and imperfect competition in the permits market, tradeable permits offer less R&D incentives than emission standards.*

Comparing auctioned permits and taxes (see eq. (27)) follows directly from the discussion between taxes and emission standards of Section 3.2. Before R&D (i.e., $k_i = 1$), direct effects are the same by regulatory design. At positive levels of R&D (i.e., $k_i < 1$), however, direct effects are larger under taxes while strategic effects may be positive under auctioned permits. For instance, if we reduce D_2' sufficiently enough so that the strategic effect from the output market under auctioned permits decreases, $-d\pi/dk$ can become greater under auctioned permits than under taxes. On the other hand, if we make the regulatory goal stricter (i.e., e is only a small fraction of q) so that the direct effect under both instruments increases, $-d\pi/dk$ can become greater under taxes than under auctioned permits. Therefore, we can establish the following proposition

Proposition 7 *Under Bertrand competition in the output market and imperfect compe-*

tition in the permits market, auctioned permits can offer more, less or the same R&D incentives than taxes.

5 Some Numerical Examples

In this section, I develop some numerical examples to illustrate and complement some of the analytical results shown in the previous sections. The examples are not randomly selected, but rather to emphasize differences between direct and strategic effects.

5.1 The social optimum: a benchmark

To compare R&D incentives under different market and regulatory structures, it is useful to start by establishing some benchmark. For that purpose, I use the optimization problem of a social planner pursuing first-best levels of output, emissions and R&D. This will also allow us to have some estimate of the divergence between private and social optimum R&D levels. However, we do not discuss R&D policies that could bring private investment to social optimum levels because that would also require discussion of competition policies, which is not the purpose of the paper.

To find the social optimum, let first h be the marginal harm caused by a unit of emission (assumed constant for simplicity but without implications for the R&D comparisons). Thus, at any given level of k_i and k_j, the first-best output and emission levels solve

$$p = k_i C_i'(q_i - e_i) \qquad (35)$$

$$k_i C_i'(q_i - e_i) = h \tag{36}$$

where p is the output price in either the Cournot or Bertrand game. In our simple model, (35) indicates that prices are equal to total marginal costs (recall that output costs are zero), and (36) indicates that marginal abatement costs must be equal to marginal damage. The first-best solution can be achieved by either setting the tax level $\tau = h$ or by issuing (or auctioning off) an amount $\overline{E}$ permits such that the equilibrium price of permits σ is equal to h (because of the symmetry of the problem, the social planner could also achieve the first-best by setting emission standards $\overline{e}$ equal to $\overline{E}/2$).

Now, for any given level of k_i and k_j, let $W(k_i, k_j) = CS(q_i, q_j) - \sum C_i(q_i - e_i) - (e_i + e_j)h$ be the optimum level of social welfare, where $CS(q_i, q_j)$ is consumer surplus, and q_i and e_i are at their first-best levels as estimated above from (35) and (36). To find the first-best levels of R&D, K_i^* and K_j^*, the social planer maximizes $W(k_i, k_j) - (K_i + K_j)v$ subject to (1). From the envelope theorem and the symmetry of the problem, the solution is given by

$$\frac{dW}{dk}\frac{\partial k}{\partial K} - 2v = -2C(q-e) \cdot f'((1+\theta)K^*) \cdot (1+\theta) - 2v = 0$$

Using the above first-best solution as a benchmark case, I start the numerical examples with Cournot competition, and then, Bertrand competition.

5.2 Cournot examples

Let $P(Q) = a - bQ$ be the demand curve and $C(q-e) = (q-e)^2$ be abatement costs before R&D, where $Q = 2q$. Let $k = f(K_T) = (1-\gamma)e^{-K_T} + \gamma$ be the R&D production function, where $0 < \gamma < 1$, $K_T = (1+\theta)K$, and K is the amount of R&D effort by each firm in the equilibrium.[18] The market and regulatory parameters are chosen to yield a significant amount of emissions abatement. To simplify matters, the regulatory design is such that before R&D, marginal abatement costs are equal to marginal harm h.

In the first example, Ex. 1, I use the following parameters: $a = 16$, $b = 0.2$, $\gamma = 0.4$, $v = 5$ and $h = 10$. Results in this and following examples are at the firm level. The first row of Table 1 ("Before R&D") shows market and regulatory characteristics before R&D takes place. The regulatory design imposes a significant reduction, $q - e$, upon firms of 50%, which is achieved by either levying a tax $\tau = 10$, issuing a total number of permits $\overline{E} = 10$, which leads to $\sigma = 10$, or setting emission standards $\overline{e} = 5$ for each firm. Note that the reason for the output price $P(Q)$ to be close to marginal costs is because the large price elasticity (-3 at the market equilibrium), which will make strategic effects to be relatively less important than direct effects. Firm's optimal R&D efforts, K, for three levels of R&D spillovers ($\theta = 0$, 0.5, and 1) and under each of the regulatory regimes (E. ST., TAX, T. P., and A. P.) are shown in the next 4 rows.[19] R&D investments are larger under taxes (TAX) than under emission standards (E. ST.) and auctioned permits (A.P.) because direct effects are more important. The parameters of the example were chosen that it is possible to have no investment under tradeable permits (T.P.).

[18] Optimal K under each regulatory regime is obtained from (2) and either (6), (10) or (19).

[19] Note that market and environmental outcomes are not affected by θ. This is because optimal k is independent of θ (see footnote 9).

Results for the benchmark case ("Social Opt.") are in the next row (values for e and k are not included because they vary with θ). Optimal R&D levels from the firm perspective are always below the social optimum in this example and more so with the degree of spillovers. Naturally, as the degree of spillovers increases, private R&D departs further from the social optimum by not considering the even higher positive externality effects of R&D. It is interesting to see that taxes with zero spillover lead to the social optimum amount of R&D. This is because marginal damage h is constant and equal to the tax level τ and marginal costs $kC'(\cdot)$ at all times regardless the amount of R&D, which implies that abatement $q - e$, and hence, the direct effect $C(q - e)$, for the firm and social planner coincide when there are no spillovers. Note that this would not be the case if marginal damage were a increasing function of emissions.

In Ex. 2, I let the demand curve to increase to $a = 22$, which significantly reduces the regulatory requirements to 25%. I also increase v from 5 to 5.6 to ensure that emissions under "Social Opt." are positive for all values of θ. This drop in the regulatory goal makes direct effect relatively less important, which leads to higher R&D under auctioned permits than under standards and taxes. Finally, in Ex. 3, I keep the 50% regulatory goal of Ex. 1 and make the demand curve more inelastic setting $a = 160$ and $b = 5$.[20] Strategic effects from the output market are now much more important than direct effects, which leads to higher R&D under standards than under taxes and auctioned permits.

[20] I also increase v to 5.7 for the same reasons above.

5.3 Bertrand examples

In the following examples, I continue using a linear demand curve and let $D_i(p_i, p_j) \equiv q_i = a - bp_i + cp_j$, where $-D'_1 \equiv b \geq c \equiv D'_2$.[21] Cost and R&D production functions remain the same. In the first example of Table 2, Ex. 1, I consider homogenous products and use the following parameters: $a = 10$, $b = 0.5$, $c = 0.5$, $\gamma = 0.4$, $v = 5.6$ and $h = 10$. With these parameters, the amount of reduction is significant and equal to 50%, as shown in the first row of Table 2 under "Before R&D." In this example (negative) strategic effects from the output market are large enough for taxes to lead to more R&D than auctioned permits. Again, R&D under taxes is equal to the Social optimum level of R&D when there are no spillovers ($\theta = 0$) by the same reasons laid out before.

In Ex. 2, I reduce the regulatory goal to 25% and use the following parameters values: $a = 20$, $b = c = 1$, $\gamma = 0.4$, $v = 5.4$. Because both direct effects and (negative) strategic effects from the output market decrease with these new values, auctioned permits not only lead to more R&D than taxes but also lead to R&D close to the social optimum level for small spillovers.

6 Concluding Remarks

In this paper, I have compared a firm's incentives to invest in environmental R&D under different market structures and environmental policy instruments. Because of market strategic effects, R&D incentives are found to vary widely across market structures and instruments. In particular, I found that when firms' products are strategic substitutes

[21] As before, optimal K under each regulatory regime is obtained from (2) and either (23), (27) or (34).

(i.e., Cournot), either emission standards, taxes or auctioned permits can provide the most incentives. But when firms' products are strategic complements (i.e., differentiated Bertrand), either taxes or auctioned permits can provide the most incentives.

A natural question that remains is how the results of the paper change as markets become more competitive. To answer this question, we can simply extend the model from two to a large number of firms competing à la Cournot. Strategic effects no longer matter, so we need only concentrate on direct effects, or more precisely, on abatement levels $q_i - e_i$. Before R&D (i.e., $k = 1$), direct effects are the same for all instruments by regulatory design. By the same arguments laid out in the paper (see Section 3.2 for example), at positive levels of R&D (i.e., $k < 1$), however, direct effects are higher under taxes than under permits and emission standards because abatement is higher. Consequently, under perfect competition, tradeable permits, auctioned permits and emission standards lead to the same amount of R&D but lower than taxes.

Additional to the above finding is that under perfect competition R&D incentives are not affected by the way the permits are initially distributed among firms, and that is why incentives under grandfathered permits auctioned permits are the same. This is in sharp contrast with previous literature (e.g., Milliman and Prince, 1989; and Jung et al, 1996), where authors fail to distinguish between cost savings (including permits payments) and innovation incentives. The reason is that for any given output price P and permits price σ, the effect of a change in k on the profits π of a price-taking firm does not depend on the distribution of permits ϵ. Even output q is not affected by changes in k, because at the margin the additional production cost from the regulation continues to be σ.

There a few extensions to the model that may be worth exploring. One extension would be to consider a different technology innovation process. It could be modeled a as patent race where R&D firms (other than production firms) compete for the invention of a more efficient technology to be sold to producing firms either because lowers production costs or because the regulator imposes firms to adopt the new technology. Note that this has already been done for the case of perfect competition in the output market (Biglaiser and Horowitz, 1995). Another interesting extension would be to consider ex-ante asymmetries among firms. Firms will often have different costs of production and costs to conduct R&D either because of size (economies of scale) or past experience. Firms may also have different costs to adopt new technologies because of previous investments or commitments like long-term contracts.

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Appendix A

Under Cournot competition and emission standards regulation, the first order conditions for firms i and j are

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - \overline{e}_i) = 0 \tag{A1}$$

$$P(Q) + P'(Q)q_j - k_j C_j'(q_j - \overline{e}_j) = 0 \tag{A2}$$

Taking total derivative with respect to k_i at the Nash equilibrium in both expressions we obtain

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_i}{dk_i} + P'' q_i \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) - C_i' - k_i C_i'' \frac{dq_i}{dk_i} = 0 \tag{A3}$$

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_j}{dk_i} + P'' q_j \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) - k_j C_j'' \frac{dq_j}{dk_i} = 0 \tag{A4}$$

Then, subtracting (A4) from (A3) and rearranging (A4), we obtain the system of equations that by symmetry reduces to

$$(P' - kC'') \frac{dq_i}{dk_i} + (-P' + kC'') \frac{dq_j}{dk_i} - C' = 0 \tag{A5}$$

$$(P' + P''q) \frac{dq_i}{dk_i} + (2P' + P''q - kC'') \frac{dq_j}{dk_i} = 0 \tag{A6}$$

which leads to

$$\frac{dq_j}{dk_i} = \frac{C' \cdot (P' + P''q)}{(P' - kC'')(-3P' - 2P''q + kC'')} \tag{A7}$$

This is the fraction of the last term in (6) in the text.

Appendix B

Under Cournot competition and permits regulation, the equilibrium conditions in the permits and output markets for firms i and j are given by

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - e_i) = 0 \tag{B1}$$

$$P(Q) + P'(Q)q_j - k_j C_j'(q_j - e_j) = 0 \tag{B2}$$

$$k_i C_i'(q_i - e_i) = k_j C_j'(q_j - e_j) = \sigma \tag{B3}$$

$$e_i + e_j - \overline{E} = 0 \tag{B4}$$

Taking total derivative with respect to k_i in all four expressions

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_i}{dk_i} + P''q_i \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - C_i' - k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i}\right) = 0 \tag{B5}$$

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_j}{dk_i} + P''q_j \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i}\right) = 0 \tag{B6}$$

$$C_i' + k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i}\right) = k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i}\right) = \frac{d\sigma}{dk_i} \tag{B7}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0 \tag{B8}$$

From (B7) and (B8), we obtain

$$\frac{de_i}{dk_i} = \frac{1}{2}\frac{dq_i}{dk_i} - \frac{1}{2}\frac{dq_j}{dk_i} + \frac{C'}{2kC''} \tag{B9}$$

$$\frac{de_j}{dk_i} = \frac{1}{2}\frac{dq_j}{dk_i} - \frac{1}{2}\frac{dq_i}{dk_i} - \frac{C'}{2kC''} \tag{B10}$$

and replacing (B9) into (B5) and (B10) into (B6), to become (B5') and (B6'), respectively, and then subtracting (B6') from (B5'), we obtain

$$\frac{dq_i}{dk_i} = \frac{dq_j}{dk_i} \tag{B11}$$

Then, to find dq_j/dk_i, we replace (B9)-(B11) into either (B5) or (B6) to obtain

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - kC'')} \tag{B12}$$

and to find $d\sigma/dk_i$, we replace (B9)-(B12) into (B7) to obtain

$$\frac{d\sigma}{dk_i} = \frac{(3P' + 2P''q)C'}{2(3P' + 2P''q - kC'')} \tag{B13}$$

Appendix C

Under Bertrand competition (regardless of whether products are homogeneous or differentiated) and emission standards regulation, the first order conditions for firms i and j are

$$D_i(p_i, p_j) + p_i \frac{\partial D_i}{\partial p_i} - k_i C_i'(D_i - \overline{e}_i) \frac{\partial D_i}{\partial p_i} = 0 \tag{C1}$$

$$D_j(p_i, p_j) + p_j \frac{\partial D_j}{\partial p_j} - k_j C_j'(D_j - \overline{e}_j) \frac{\partial D_j}{\partial p_j} = 0 \tag{C2}$$

Taking total derivative with respect to k_i at the Nash equilibrium in both expressions, rearranging, assuming symmetry and using the simplified notation (see text) gives

$$A\frac{dp_i}{dk_i} + B\frac{dp_j}{dk_i} - D_1'C' = 0 \tag{C3}$$

$$B\frac{dp_i}{dk_i} + A\frac{dp_j}{dk_i} = 0 \tag{C4}$$

where $A = (2D_1' - k(D_1')^2C'' + (p - kC')D_{11}'')$ and $B = (D_2' - kD_1'D_2'C'' + (p - kC')D_{12}'')$. Second order conditions (SOCs) for a local maximum require that $A < 0$ and $A^2 - B^2 > 0$.

Since $B > 0$, the SOCs also imply that $A + B < 0$.

Subtracting (C4) from (C3) and rearranging, we obtain

$$\frac{dp_j}{dk_i} = \frac{-BD_1'C'}{A^2 - B^2} \tag{C5}$$

which is positive since $D_1' < 0$ and $D_{12}'' > 0$. This is part of the last term in (23) in the text. Note that if the demand curve $D(p_i, p_j)$ is linear (i.e., $D_{12}'' = D_{11}'' = 0$) it is immediate that $A < 0$, $B > 0$, $A + B < 0$ and $dp_j/dk_i > 0$.

Appendix D

Under Bertrand competition (regardless of whether products are homogeneous or differentiated) and permits regulation, the equilibrium conditions in the permits and output markets for firms i and j are given by

$$D_i(p_i, p_j) + p_i\frac{\partial D_i}{\partial p_i} - k_iC_i'(D_i - e_i)\frac{\partial D_i}{\partial p_i} = 0 \tag{D1}$$

$$D_j(p_i, p_j) + p_j\frac{\partial D_j}{\partial p_j} - k_jC_j'(D_j - e_j)\frac{\partial D_j}{\partial p_j} = 0 \tag{D2}$$

$$k_iC_i'(q_i - e_i) = k_jC_j'(q_j - e_j) = \sigma \tag{D3}$$

$$e_i + e_j - \overline{E} = 0 \tag{D4}$$

Taking total derivative with respect to k_i in all four expressions (and assuming symmetry)

$$A\frac{dp_i}{dk_i} + B\frac{dp_j}{dk_i} + D_1' kC'' \frac{de_i}{dk_i} - D_1' C' = 0 \tag{D5}$$

$$B\frac{dp_i}{dk_i} + A\frac{dp_j}{dk_i} + D_1' kC'' \frac{de_j}{dk_i} = 0 \tag{D6}$$

$$C' + kC'' \cdot \left(D_1' \frac{dp_i}{dk_i} + D_2' \frac{dp_j}{dk_i} - \frac{de_i}{dk_i} \right) = kC'' \cdot \left(D_2' \frac{dp_i}{dk_i} + D_1' \frac{dp_j}{dk_i} - \frac{de_j}{dk_i} \right) = \frac{d\sigma}{dk_i} \tag{D7}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0 \tag{D8}$$

where A and B are as in Appendix C. From (D7) and (D8), we obtain

$$\frac{de_i}{dk_i} = \frac{D_2' - D_1'}{2} \left(\frac{dp_j}{dk_i} - \frac{dp_i}{dk_i} \right) + \frac{C'}{2kC''} \tag{D9}$$

$$\frac{de_j}{dk_i} = \frac{D_2' - D_1'}{2} \left(\frac{\partial p_i}{\partial k_i} - \frac{\partial p_j}{\partial k_i} \right) - \frac{C'}{2kC''} \tag{D10}$$

and replacing (D9) into (D5) and (D10) into (D6), to become (D5') and (D6'), respectively, and then subtracting (D6') from (D5'), we obtain

$$\frac{dp_i}{dk_i} = \frac{dp_j}{dk_i} \tag{D11}$$

Then, to find dp_j/dk_i, we replace (D9)-(D11) into either (D5) or (D6) to obtain

$$\frac{dp_j}{dk_i} = \frac{D_1'C'}{2(A+B)} \tag{D12}$$

which is positive from the second order conditions discussed in Appendix C. Finally, to find $d\sigma/dk_i$, we replace (D9)-(D12) into (D7) to obtain

$$\frac{d\sigma}{dk_i} = \frac{kC''}{2}\left(\frac{(D_1'+D_2')D_1'C'}{A+B} + \frac{C'}{kC''}\right) \tag{D13}$$

It is not difficult to demonstrate that this expression is unambiguously positive when either products are homogeneous (i.e., $D_1' + D_2' = 0$) or the demand curve is linear (i.e., $D_{11}' = D_{12}' = 0$).

Table 1. R&D under Cournot competition

							K		
Ex.	Scenario	τ, σ	q	$P(Q)$	e	k	$\theta = 0$	$\theta = 0.5$	$\theta = 1$
1	Before R&D	10	10	12	5	1	–	–	–
	E. ST.	n.a.	11.35	11.46	5	0.72	0.620	0.413	0.310
	TAX	10	10	12	1.5	0.59	1.161	0.774	0.581
	T. P.	10	10	12	5	1	0	0	0
	A. P.	10	11.42	11.43	5	0.71	0.652	0.435	0.326
	Social Opt.	10	15	10			1.161	1.300	1.180
2	Before R&D	10	20	14	15	1	–	–	–
	E. ST.	n.a.	20.74	13.70	15	0.83	0.327	0.218	0.164
	TAX	10	20	14	12.75	0.69	0.729	0.486	0.365
	T. P.	10	20	14	15	1	0	0	0
	A. P.	8.81	21.99	13.21	15	0.63	0.958	0.638	0.479
	Social Opt.	10	30	10			0.729	1.178	1.102
3	Before R&D	10	10	60	5	1	–	–	–
	E. ST.	n.a.	10.18	58.16	5	0.70	0.701	0.467	0.351
	TAX	10	10	60	3.18	0.73	0.589	0.393	0.295
	T. P.	10	10	60	5	1	0	0	0
	A. P.	10	10.08	59.20	5	0.87	0.254	0.169	0.127
	Social Opt.	10	15	10			0.589	1.158	1.090

Table 2. R&D under Bertrand competition

							K		
Ex.	Scenario	τ, σ	q	p	e	k	$\theta = 0$	$\theta = 0.5$	$\theta = 1$
1	Before R&D	10	10	10	5	1	–	–	–
	E. ST.	n.a.	10	10	5	1	0	0	0
	TAX	10	10	10	2.75	0.69	0.729	0.486	0.365
	T. P.	7.71	10	10	5	1	0	0	0
	A. P.	7.87	10	12.13	5	0.79	0.439	0.293	0.219
	Social Opt.	10	10	10			0.729	1.178	1.102
2	Before R&D	10	20	10	15	1	–	–	–
	E. ST.	n.a.	20	10.04	15	1	0.007	0.005	0.004
	TAX	10	20	10	12.21	0.64	0.908	0.605	0.454
	T. P.	9.96	20	10.04	15	1	0.006	0.004	0.003
	A. P.	6.32	20	13.68	15	0.63	0.949	0.633	0.475
	Social Opt.	10	20	10			0.918	1.218	1.128