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Summary

We examine the relationship between competition and innovation in an industry where production is polluting and R&D aims to reduce emissions ("green" innovation). We present an n-firm oligopoly where firms compete in quantities and decide their investment in "green" R&D. When environmental taxation is exogenous, aggregate R&D investment always increases with the number of firms in the industry. Next we analyse the case where the emission tax is set endogenously by a regulator (committed or time-consistent) with the aim to maximise social welfare. We show that an inverted-U relationship exists between aggregate R&D and industry size under reasonable conditions, and is driven by the presence of R&D spillovers.

Keywords: "Green" R&D, R&D Spillovers, Emission Taxation, Time-Consistent Emission Tax, Pre-Committed Emission Tax
JEL Classification: Q55, Q56, O30, L13

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Abstract

We examine the relationship between competition and innovation in an industry where production is polluting and R&D aims to reduce emissions (“green” innovation). We present an n-firm oligopoly where firms compete in quantities and decide their investment in “green” R&D. When environmental taxation is exogenous, aggregate R&D investment always increases with the number of firms in the industry. Next we analyse the case where the emission tax is set endogenously by a regulator (committed or time-consistent) with the aim to maximise social welfare. We show that an inverted-U relationship exists between aggregate R&D and industry size under reasonable conditions, and is driven by the presence of R&D spillovers.

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Keywords: “green” R&D, R&D spillovers, emission taxation, time-consistent emission tax, pre-commited emission tax.

1 Introduction

The link between competition and innovation has long been debated among economists. Theories of industrial organisation usually predict that innovation should decline with competition (Schumpeter, 1942). There are several arguments supporting the view that possession of market power should result in greater innovative activities. First, market power may be extendable to new products, for example, through a dominant firm's command over channels of distribution, and so on. With the ability to extend market power to new products, an incumbent monopolist should find innovation more attractive. Second, there may be a need to finance innovation internally, which puts firms with market power at an advantage since these firms may have supernormal profits. Third, firms with current market power typically have more resources and thus are more likely to hire the most innovative people. Of course the third argument is related to the imperfect capital market argument underlying the second reason.

However, theoretical research also indicates that a monopolist can have reduced incentives to innovate. Arrow (1962) shows that a competitor can profit more than a monopolist from innovation, and the monopolist may be slower in replacing it with a superior product or process than a newcomer. This is because the firm realising monopoly profits on its current product calculates the profit from innovation as the difference between its current profits and the profits it could realise from the new product, whereas the competitor regards the profits from the new product as the gain. As such, the larger current monopoly profits are, the less incentive the monopolist has to innovate. Moreover, a monopolist may regard additional leisure as superior to additional profits. This may be due to the lack of active competitive forces and thus generates an x-inefficiency effect.

The lively debate on the relationship between competition and innovation is still open both in the theoretical and empirical literature. Theoretical works comparing a monopolist's and an entrant's incentives to innovate also provide mixed predictions about the impact of monopoly power on innovative effort. Factors such as uncertainty in the innovation process and the strategic relation between new and existing products may motivate entrants to spend more on R&D relative to incumbents. The early empirical literature showed no clear-cut results in the relationship between market structure and innovative activity.[1] Subsequently, a large evidence showing an increase of innovation with competition has been uncovered.[2] According to these results, technological opportunity is what largely determines innovative activity and must be controlled for when investigating the relationship between market structure and innovation.[3]

In a more recent contribution, Aghion *et al.* (2005) provide evidence of an inverted-U relationship between innovation and competition. Their theoretical explanation is based on Aghion *et al.* (1997), a neo-Schumpeterian growth model, in which both technological leaders and followers in any industry can

[1] See Kamien and Schartz (1982) for an extensive discussion.

[2] e.g., see Levin *et al.* (1985), Cohen *et al.* (1987), Cohen and Levin (1989), Geroski (1990), Blundell *et al.* (1995, 1999). In a recent study on market concentration and innovation in Central and Eastern Europe, Voinea and Stephan (2009) shows that competition enhances knowledge creation.

[3] Some empirical work considers the possibility that R&D intensity and market structure are both determined by other market characteristics. Levin and Reiss (1984, 1988) analyse R&D and concentration in simultaneous equations models controlling for technical opportunity and appropriability conditions. According to Symeonidis (1996), R&D intensity and market structure are jointly determined by technology, demand characteristics, the institutional framework, strategic interaction and chance.

innovate, and innovations occur as a step-by-step process.[4] Innovation incentives depend upon the difference between post-innovation and pre-innovation rents of incumbent firms. In this case, more competition may foster innovation and growth, because it may reduce a firm's pre-innovation rents by more than it reduces its post-innovation rents.

One aspect that, to the best of our knowledge, has not been considered is the relationship between competition and innovation in a polluting industry where R&D investment aims to reduce the environmental impact of production. This is the purpose of the present paper. In particular, we verify the presence of an inverted-U relationship between competition and innovation in a microeconomic setting of oligopolistic competition where production is polluting and innovation results in reducing emissions (abatement, "green" R&D). Given the presence of Pigouvian (emission) taxation, reducing pollution would reduce production costs.[5] We present an n-firm oligopoly model where firms compete in quantities and decide their investment in "green" R&D, and spillovers in R&D are present. We establish the link between competition and "green" innovation through the variation of aggregate investment in R&D according to the number of firms in the industry: a greater number of firms in the industry proxies increased competition and a concomitant reduction in market power (Sutton, 1998). We consider three different scenarios. First, we consider the case where emission taxation is exogenous. Our results show a strong Arrowian flavour, i.e., aggregate R&D investment monotonically increases with the number of firms. Next we consider the presence of an environmental regulator that sets the optimal tax on pollution. We examine both cases according to whether

[4] See also Scott and Scott (2014) for a more traditional IO interpetation of the inverted-U relationship.

[5] The introduction of Pigouvian taxation by a regulator dates back to Keeler *et al.* (1971), and has been extensively examined in the literature.

the regulator can commit or cannot commit credibly (time-consistent) to the taxation policy (Petrakis and Xepapadeas (2001, 2003), and Golombek *et al.* (2010)). With endogenous taxation we show that the relationship between competition and "green" R&D is represented by an inverted U. We show that this result is driven by the presence of R&D spillovers and establish the necessary conditions. The results obtained by Aghion *et al.* (2005) are thus confirmed in a microeconomic framework where innovation has the aim of abating polluting emissions.

The paper is also related to the literature on organisational structure of environmental R&D, cooperative versus independent (e.g., Scott (1996), Chiou and Hu (2001), Petrakis and Poyago-Theotoky (2002), Sandonís and Mariel (2004), Poyago-Theotoky (2007), and Golombek and Hoel (2008)). With this literature, we share the assumption of R&D efforts being directed not towards process or product enhancement, but directed towards emission reduction of harmful pollutants. The analysis in the paper is close to Poyago-Theotoky (2007), who examines the issue of R&D cooperation vs competition in a polluting industry where two firms operate and endogenous taxation is set by a pre-committed regulator. Compared to Poyago-Theotoky (2007), we set aside the R&D cooperation issue; instead we consider an oligopoly rather than a duopoly, and we also analyse the case in which the regulatory policy is time-consistent.[6]

[6]Furthermore, the paper is related to the literature of innovation and market structure. Hausman and MacKie-Mason (1988) argued that the actions of monopolies with regards to third-degree price discrimination, may lead to social welfare improvement due to opening new markets, achieving economies of scale and higher efficiency and, importantly, increasing net social welfare. Geroski and Pomroy (1990) show that innovating may be a way to obtain market power, in particular they find that innovation increases the degree of competition in markets. This leads to a fall in market concentration over time and eventually to the emergence of very few and large firms. Therefore firms innovate with the aim to become incumbents. Etro (2004) shows that the innovative process is naturally connected to the persistence of monopolies. Their investment in research and development would be benefi-

The remainder of the paper is organised as follows. Section 2 presents the model, section 3 establishes the results and section 4 concludes.

2 The model

Consider an oligopoly market with n profit-maximising firms competing *à la* Cournot-Nash. Firms supply a homogeneous good, with market demand given by $p = a - Q$, a being a positive constant parameter measuring the reservation price (alternatively, the size of the market) and $Q = \sum_{i=1}^{n} q_i$ being the sum of all firms' individual output levels q_i. Production generates pollution, which is taxed at the emission tax rate t, while firm i can reduce its tax burden by undertaking environmental(“green”) R&D, z_i, to reduce its emissions. The cost function for firm i is given by $c(q_i, z_i) = cq_i + \gamma z_i^2/2$, where c is the unit cost of production, $a > c$, and $\gamma > 0$ is a parameter measuring the effectiveness of R&D. Firm's i emissions are

$$e_i(q_i, z_i) = q_i - z_i - \beta \sum_{j \neq i}^{n} z_j > 0, \tag{1}$$

where $\beta \in [0, 1]$ represents R&D spillovers. We denote aggregate R&D as $Z = \sum_{i=1}^{n} z_i$ and the total investment in R&D as $\gamma Z^2/2$. Hence firm i's profit function is $\pi_i = pq_i - c(q_i, z_i) - te_i(q_i, z_i)$, so that taxation is a linear function of emissions. Total emissions are $E = \sum_{i=1}^{n} e_i(q_i, z_i)$, and the damage function is a quadratic function of emissions, $D = dE^2$, where d is a parameter capturing the steepness of marginal damages or, the degree of convexity of the damage function. To guarantee interior solutions in what follows we assume

cial to society as they advance new technologies. Our paper contributes to this strand by focussing on innovation with “green” features.

$d > (1/2n)$ (see also, Petrakis and Xepapadeas (2001, 2003) Poyago-Theotoky (2007). This implies that environmental damages are not insignificant for the economy. Finally, total tax revenue is $T = t\sum_{i=1}^{n} e_i$, whereas consumer surplus is measured by $CS = Q^2/2$. Social welfare is defined in the standard way as the sum of industry profits and consumer surplus, plus tax revenue, minus environmental damages:

$$W = \sum_{i=1}^{n} \pi_i + \frac{Q^2}{2} + T - dE^2. \tag{2}$$

For notational simplicity we shall define market size as $m = a - c$.

We separately consider three different cases. In the first case, taxation is exogenous. In this scenario, there is a two-stage game where firms non-cooperatively choose their investment in green R&D in the first stage and compete in quantities in the second stage. We then introduce endogenous taxation determined by a regulator with the aim of maximising social welfare. In particular, in the second case, the regulator pre-commits to the environmental policy. In other words, the optimal emission tax does not react to firms’ decisions on R&D, but it is pre-determined. The associated game is now a three-stage game where, in stage one, the regulator sets the emission tax so as to maximise social welfare, in stage two, firms invest in green R&D and in stage three market competition occurs. In the third case, environmental regulation is time-consistent. This implies that the optimal tax adapts to the level of investment in R&D. Therefore, R&D investment takes place in stage one and the welfare-maximising taxation in stage two, followed by output competition in stage three. The equilibrium concept is perfect subgame equilibrium with backward induction.

3 Analysis and Results

We begin by examining the market competition stage which is common to all three cases considered. Firm i chooses output to maximise profits

$$\max_{q_i}[pq_i - c(q_i, z_i) - te_i(q_i, z_i)].$$

From the first-order condition, $a - 2q_i - q_{-i} - c - t = 0$, where $q_{-i} = \sum_{j \neq i} q_j$, and by symmetry (i.e. $q_1 = q_2 = ... = q_n \equiv q_i^*$) we obtain per-firm equilibrium output:

$$q_i^* = \frac{m - t}{1 + n}.$$

Notice that the equilibrium quantity does not depend on abatement directly, but it is affected by it through taxation. The equilibrium profit is:

$$\pi_i^* = \frac{2(m-t)^2 + (1+n)^2\left[2t\left(z_i + \beta \sum_{j \neq i}^n z_j\right) - \gamma z_i^2\right]}{2(1+n)^2}, \quad (3)$$

and is the same in each configuration considered below.

3.1 Exogenous taxation

Consider first the case with exogenous taxation, where, in the first stage, firm i chooses green R&D (abatement). Using (3), obtaining the first-order condition and solving yields equilibrium R&D, $z_i^* = t/\gamma$, equal to the unitary tax adjusted for R&D efficiency. Thus aggregate R&D is:

$$Z_1^* = \frac{nt}{\gamma},$$

where the subscript 1 represents the case considered. Clearly, total R&D increases monotonically with the number of firms in the market: with exogenous taxation we obtain a clear-cut Arrowian result. Increased competition (higher n) leads to an increase in aggregate R&D (innovation). Summarising we have,

Proposition 1 *With exogenous taxation, there is a positive relationship between competition and "green" R&D.*

3.2 Optimal pre-committed emission tax

Consider next the cases with endogenous taxation. In the second configuration, the regulator pre-commits to its environmental policy. Compared to the case with exogenous taxation, now there is a stage (stage 1) before the R&D investment stage in which the regulator sets the emission tax so as to maximise social welfare. Solving the associated game fully, yields the optimal pre-commitment emission tax:

$$t_2^* = \frac{m\gamma n\left[2d\left(n+1+\beta\left(n^2-1\right)\right)+\gamma\left(2d-1/n\right)\right]}{n\gamma^2\left(1+2d\right)+\gamma\left(1+n\right)\left[1+n\left(1+4d\left(1+\beta\left(n-1\right)\right)\right)\right]+2dn\left[n+1+\beta\left(n^2-1\right)\right]^2}.$$

Aggregate R&D is given by:

$$Z_2^* = \frac{mn\left[2d\left(n+1+\beta\left(n^2-1\right)\right)+\gamma\left(2d-1/n\right)\right]}{\gamma^2\left(1+2d\right)+\gamma\left(1+n\right)\left[1+n\left(1+4d\left(1+\beta\left(n-1\right)\right)\right)\right]+2dn\left[n+1+\beta\left(n^2-1\right)\right]^2}.$$

A sufficient condition for Z_2^* to be non-negative is $d > (1/2n)$, which is satisfied by assumption.

In order to obtain fully analytical results, we then evaluate the shape of the aggregate R&D function: given Z_2^* is a continuous function in n, if the first derivative is positive for a small number of firms (say $n = 1$), and the limit of the function when n tends to infinity is zero; then from the Rolle and Mean

Value Theorems[7] the total R&D function entails an inverted-U shape. The first derivative of Z_2^* with respect to n when $n = 1$ is:

$$\left.\frac{\partial Z_2^*}{\partial n}\right|_{n=1} = \frac{2dm\left[2d\left(1+\gamma-2\beta\right)\left(2+\gamma\right)^2+\gamma\left(16+\gamma\left(9+\gamma\right)+2\beta\left(8+3\gamma\right)\right)\right]}{\left[2d\left(2+\gamma\right)^2+\gamma\left(4+\gamma\right)\right]^2}. \quad (4)$$

The sufficient condition under which (4) is positive is

$$\gamma > \widetilde{\gamma} \equiv 2\beta - 1.$$

Consider next the limit of Z_2^* and $\partial Z_2^*/\partial n$ when n tends to infinity:

$$\lim_{n\to+\infty} Z_2^* = 0, \ \lim_{n\to+\infty} \frac{\partial Z_2^*}{\partial n} = 0.$$

Therefore it is evident that the aggregate R&D function with respect to the number of firms in the industry features an inverted U, yielding a Schumpeterian flavoured result which can be summarised as follows.

Proposition 2 *Consider endogenous taxation and a pre-committed regulator. Suppose $\gamma > \widetilde{\gamma}$. Then aggregate R&D presents the shape of an inverted U with respect to the number of firms (Figure 1).*

[7]See Apostol (1967) for details.

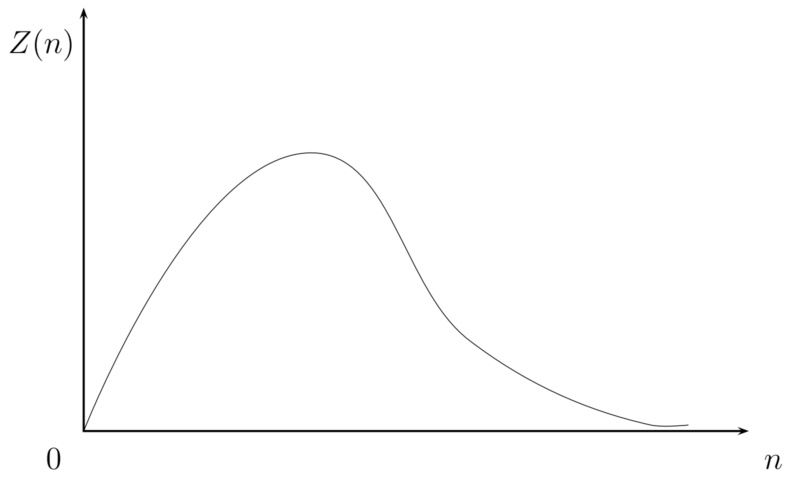

Figure 1: An inverted-U relationship

In order to highlight the role of R&D spillovers, consider the case with no spillovers, $\beta = 0$. Total R&D is

$$Z_2^*|_{\beta=0} = \frac{m\left[2dn\left(n+1+\gamma\right)-\gamma\right]}{\gamma^2\left(1+2d\right)+\gamma\left(1+n\right)\left[1+n\left(1+4d\right)\right]+2dn\left(n+1\right)^2},$$

and the first derivative of $Z_2^*|_{\beta=0}$ with respect to n is:

$$\begin{aligned}\left.\frac{\partial Z_2^*}{\partial n}\right|_{\beta=0} &\propto 4d\gamma n\left(1+\gamma\right)+n^2\left[4d^2\left(1+\gamma\right)^3+2d\gamma\left(7+\gamma\left(5+\gamma\right)\right)\right]+\\ &\quad +4dn^3\left[2d\left(1+\gamma\right)^2+\gamma\left(3+\gamma\right)\right]+\\ &\quad 2dn^4\left[\gamma+2d\left(1+\gamma\right)\right]+\gamma^2n^2-\gamma^2\\ &> 0,\end{aligned}$$

showing a positive relationship between innovation and n, that is, a clear-cut Arrowian result.

Corollary 1 *Consider endogenous taxation, pre-committed policy and no R&D spillovers. Then there is a positive relationship between competition and "green" R&D.*

Corollary 1 points out that the inverted-U relationship is driven by the presence of spillovers. It also provides an intuition for the result of Proposition 1, since an exogenous tax does not transfer the effect of spillovers in the aggregate R&D schedule.

It appears then that it is the presence of spillovers that is the main driving force for the inverted-U relationship between competition and innovation (Proposition 2). In the absence of spillovers, firms appropriate fully the results of their R&D, and can thus use these results towards reducing pollution and their emission tax bill. When spillovers are present, firms suffer from the appropriability problem (R&D results leak out to rivals without payment) which also erodes market share and unless they have significant market power (i.e., a low n) they are lead to cut on innovation expenditure, so that aggregate R&D exhibits an inverted-U shape.

3.3 Optimal time-consistent emission tax

Consider next the case in which the regulator adopts a time consistent environmental policy. In this case, the welfare-maximising tax rate is determined in the second stage, after firms have set their green R&D:

$$t_3(z_i) = \frac{m(2dn+1) - d\sum_{i=1}^{n} z_i (n+1)[1+\beta(n-1)]}{n(1+2d)}.$$

In the first stage firm i chooses R&D. Using the above and solving for z_i yields the total amount of R&D in equilibrium as:

$$Z_3^* = \left[\frac{m\left[2d\left(2+2\beta\left(n-1\right)+n\left(n+2dn-1\right)\right)-n\right]}{\begin{array}{r}\gamma n+2d\left(1+\beta^2\left(1+n\right)\left(n-1\right)^2+\beta\left(1+n\right)\left(2+n\right)\left(n-1\right)+n\left(2+2\gamma+n\right)\right)+\\ 4d^2\left(\beta^2\left(n-1\right)^3-1+n\left(n+2+\gamma\right)+\beta\left(n-1\right)\left(n\left(3+n\right)-2\right)\right)\end{array}} \right] \tag{5}$$

We then verify the relationship between competition and innovation by following the same procedure as in the pre-committment case. The first derivative of Z_3^* with respect to n evaluated at $n = 1$ is:

$$\left.\frac{\partial Z_3^*}{\partial n}\right|_{n=1} = \frac{\left[2d\left(1+2\beta+4d\right)-1\right]\left[\gamma+4d^2\left(2+\gamma\right)+2d\left(4+2\gamma\right)\right]}{\left[\gamma+4d^2\left(2+\gamma\right)+2d\left(4+2\gamma\right)\right]^2} -$$

$$\frac{\left[2d\left(2+2d\right)-1\right]\left[\gamma+2d\left(\beta\left(6+4d\right)+2\left(2+\gamma+d\left(4+\gamma\right)\right)\right)\right]}{\left[\gamma+4d^2\left(2+\gamma\right)+2d\left(4+2\gamma\right)\right]^2}. \tag{6}$$

Since the denominator is positive, we focus on the sign of the numerator of (6). By collecting γ and rearranging:

$$\left.\frac{\partial Z_3^*}{\partial n}\right|_{n=1} \propto \gamma\left(1+2d\right)^2 2d\left(2\beta+2d-1\right) - 4d\left[2d\left(1+2d\right)+\beta\left(2d\left(1+6d+4d^2\right)-3\right)\right].$$

This is positive for

$$\gamma > \widehat{\gamma} \equiv \frac{4d\left(1+2d\right)+2\beta\left[2d\left(1+6d+4d^2\right)-3\right]}{\left(1+2d\right)^2\left(2\beta+2d-1\right)} > 0,$$

for all $d > 1/2n = 1/2$, $\beta \in (0,1)$.

Consider next the limit of Z_3^* and $\partial Z_3^*/\partial n$ when n tends to infinity:

$$\lim_{n\to+\infty} Z_3^* = 0, \ \lim_{n\to+\infty} \frac{\partial Z_3^*}{\partial n} = 0$$

so that we can conclude that there is an inverted-U relationship between competition and innovation. In summary:

Proposition 3 *Consider endogenous taxation and time-consistent policy. Suppose $\gamma > \widehat{\gamma}$. Then aggregate R&D presents the shape of an inverted U with respect to the number of firms.*

As previously, we then consider the case with $\beta = 0$. In the time-consistent case, total investment in R&D is

$$Z_3^*|_{\beta=0} = \frac{m\left[2d\left(2+n\left(n+2dn-1\right)\right)-n\right]}{\gamma n+2d\left(1+n\left(2+2\gamma+n\right)\right)+4d^2\left(n\left(n+2+\gamma\right)-1\right)},$$

and the first derivative of $Z_3^*|_{\beta=0}$ with respect to n is:

$$\begin{aligned} \left.\frac{\partial Z_3^*}{\partial n}\right|_{\beta=0} &= \left(n^2-1\right)\left(1+6d\right)+2d\gamma n^2+2\gamma\left(dn^2-1\right)\left(1-2d\right)+4dn\left(2dn-2d-1\right) \\ &> 0. \end{aligned}$$

In the absence of spillovers there is no inverted-U relationship, instead we find an Arrow effect in that aggregate innovation increases with the number of firms, similarly to the pre-committent case (and with a similar intuition). With time-consistent policy, the inverted-U effect is again driven by the presence of spillovers.

Corollary 2 *Consider endogenous taxation, time consistent policy and no spillovers. Then there is a positive relationship between competition and "green" R&D.*

We then compare the critical values of γ in the pre-committed and time-consistent regime, i.e., the necessary values to trigger the inverted U relationship between competition and innovation. The difference between $\widehat{\gamma}$ and $\widetilde{\gamma}$

yields:

$$\widehat{\gamma}-\widetilde{\gamma}\propto(1+2d)\left[4d(1+d)-4\beta^{2}(1+2d)\right]+2\beta\left[4d(2+3d)-1\right]>0,$$

for all $d>1/2n$, $\beta\in(0,1)$. Therefore,

Corollary 3 *The inverted U relationship between competition and “green” innovation emerges for lower values of R&D effectiveness in the pre-committment regime.*

4 Concluding remarks

We have explored the relationship between competition and innovation when R&D investment aims at reducing polluting emissions. The problem is tackled from a microeconomic angle, through the analysis of an oligopoly where n firms compete *à la* Cournot and decide their investment in green R&D. In the case in which environmental taxation is exogenous, we show a clear-cut Arrowian result, according to which green innovation always increases with the number of firms in the industry, a proxy for increased competition. With endogenous taxation, we show that an inverted-U relationship emerges and is driven by the presence of spillovers, irrespective of whether the regulator follows a time-consistent policy or is pre-committed to the emission tax.

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