Entry Deterrence and Environmental Regulation*

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Abstract

This paper analyses how environmental regulation can be used by an incumbent firm to deter entry to an industry manufacturing a product which uses a natural resource. The model shows how the threat of entry causes the incumbent to increase both sales and the resource dependence of its product. This forces rivals out of the market as the regulatory limit on total resource use is reached; in this way, the incumbent can protect the value of any future patents on substitute products. The specific example of accumulation of agricultural chemicals in groundwater is considered. A case study of herbicide use in Italy provides qualitative support for the theory.

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1. Introduction

For an incumbent firm to deter entry to an industry, it must be able to commit credibly to a strategy that makes entry unprofitable or impossible for its rivals. Credible commitment often can be achieved through irreversible changes in capital stocks. For example, in Dixit (1980), the incumbent increases its stock of sunk physical capital in order to commit to an output level that deters entry. Mookherjee and Ray (1986) show that learning-by-doing can build up a stock of knowledge which allows an established firm to gain a cost advantage over potential entrants. Costs to consumers of switching supplier can be used by an incumbent firm to deter entry; see Klemperer (1987, 1989). (This list of examples is by no means exhaustive; see Gilbert (1989) for an excellent survey.)

Natural resource stocks provide a means by which firms can make credible commitments. The simplest example (analysed by Mason and Polasky (1994)) involves the extraction of a non-renewable natural resource.[1] In a two period model, a firm will enter the extraction industry in the second period only if costs are low enough for entry to be profitable. If extraction costs are decreasing in the stock of the resource, then entry will occur only if there is a sufficient stock of the resource remaining in the second period. An incumbent may find it optimal, therefore, to increase first period extraction to raise second period costs and so deter entry. The depletion of the non-renewable resource is irreversible and provides a credible mechanism for entry deterrence.

A more complex example of strategic behaviour in natural resource markets in-

[1] Mason and Polasky deal with the more general case of a renewable natural resource; but the basic argument is the same and is clearer when the resource is exhaustible.

volves incentives for research and development. In a series of articles (Dasgupta (1981), Stiglitz and Dasgupta (SD) (1981), Dasgupta and Stiglitz (1981), Dasgupta, Gilbert and Stiglitz (DGS) (1982), SD (1982) and DGS (1983)), the dependence of the dynamics of invention and innovation on market structure has been investigated. This work shows the effect of market structure on the rate of depletion of a natural resource and the invention and innovation dates of a backstop technology. They find that pure monopolies delay innovation relative to perfect competition; but that results for 'limited competition' (e.g. where the resource is owned by a competitive industry but a monopolist owns the substitute) do not necessarily lie in between those for polar market structures.

This paper adapts the models of DGS to investigate how an incumbent firm can use environmental regulation to deter entry. Like DGS, it considers sales of a product which uses a natural resource when there is an alternative backstop product which is more expensive, but is not resource-dependent. There are three major differences, however, between the model presented here and those found in DGS. First, we assume that the resource is sufficiently abundant that firms attach no Hotelling rents to its use. A regulator is concerned, however, about over-exploitation of the resource and so imposes restrictions on total use of the resource. The paper investigates how such regulation creates resource rents and an opportunity for entry deterrence. Secondly, we are interested in a particular form of limited competition: an incumbent firm holds patents on two substitute products, but is faced with entry when the patent on the first product expires. We examine how the incumbent may deter entry in order to protect the value of the second patent. Thirdly, in this model the incumbent is able to choose the degree of resource dependence of the first product (in DGS, one unit of output requires one unit of the resource as input). We show how strategic behaviour distorts the optimal choice of resource dependence of the product.

The use of regulation by the incumbent firm to limit competition is examined in two propositions. Proposition 1 relates the incumbent's behaviour to the familiar industrial economics classification of blockaded, accommodated and deterred entry. It gives the conditions under which the incumbent will increase sales of the resource-dependent product in order to force rivals firms out of the market. Proposition 2 shows that the incumbent may choose to manufacture products which are more resource-dependent in order to exploit entry deterring opportunities. Taken together, the results show how the incumbent can drive rivals out of the market for the first product by ensuring that the regulatory limit on resource use is reached. Clearly, this reduces profits from the first product; but the elimination of competition increases the incumbent's profits from sales of the second product.

A specific case illustrates these general propositions. Consider a patent-holding incumbent selling a product which accumulates in a natural resource. (There are many examples: agricultural chemicals in groundwater; chlorofluorocarbons (CFCs) in the atmosphere; heavy metals such as cadmium and lead in the organic chain.) A common regulatory response to accumulative pollution is to ban further use of the product once its concentration in the resource exceeds a critical level known as the maximum acceptable concentration (MAC).[2] The objective of the MAC/product ban

[2] Rölike (1996) reports that by 1993, 78 countries had instituted this type of ban. For example, DDT was withdrawn from use in many developed countries in the 1970s. In the Federal Republic of Germany, three hundred of the (approximately) one thousand pesticides registered have been banned individually. Many European countries have responded to an EC Directive on drinking water by banning the sale and use of particular chemicals; see Bergman and Pugh (1994), and section 3, for a discussion of this regulation in Italy.

is to reduce environmental pollution by two means: first, by removing from use the particular product already present at high concentrations; and secondly, by providing a signal of society's disapproval of excessive accumulation. The paper's results show that environmental regulation may only exacerbate the problems that it is intended to solve. Imposition of MAC regulation may cause the incumbent to increase the rate of accumulation of its product in the environment. This leads to the product being banned more quickly, protecting the value of any future patents that the incumbent might win.

The paper is structured as follows. Section 2 develops a model to analyse the incentives for industry using a natural resource subjected to quantitative restrictions on resource use. Section 3 presents a case study of agricultural chemical regulation in Italy to assess whether there is any support for the models' predictions. Section 4 concludes; proofs of the propositions are provided in the appendix.

2. A Model of Entry Deterrence and Regulation

The model developed in this section is based on Stiglitz and Dasgupta (1982); its components are as follows:

The Product Market

The model runs over the life-time of two products. The first has a constant unit production cost, without loss of generality set equal to zero. Sales of this product at time t are denoted $x(t)$; it is introduced to the market at $t = 0$ and sold under monopoly by the incumbent until $t = t^*$ (the duration of a patent). At this time, other manufacturers are allowed to enter the market; they imitate the first product and the market becomes perfectly competitive. The second product is more expensive: its constant unit cost of production is $c > 0$; sales are denoted $y(t)$. The timing of invention is not of direct interest here. The simplest possible scenario has the second product being invented and innovated at a known fixed time τ, with the incumbent also being the winner of the race for the patent. (See Gilbert and Newbery (1982) for a model of patent races in which this outcome holds.) To limit the model to one 'cycle', it is assumed that the patent on the backstop has an infinite life. The two products are perfect substitutes, with a market demand function of $D(p) \geq 0$ where p is the price. The demand function is downward sloping ($D'(p) < 0$), and the price elasticity of demand $\epsilon = -\frac{p}{D}D'$ is assumed not to decrease with quantity i.e. $\frac{d\epsilon}{dQ} \geq 0$. Since the analysis is concerned with the effects of imperfect competition, $\epsilon > 1$ in the regions of interest. Inverse demand is $p(Q) = D^{-1}(Q)$; the choke-off price is assumed to be infinite i.e. $\lim_{Q \to 0} p(Q) = \infty$.

The Natural Resource

The first product uses a natural resource. One unit of the product uses $A \in [\underline{A}, 1]$ units of the natural resource, where $\underline{A} > 0$. A will be referred to as the 'usage rate'; two examples will help to illustrate its meaning. In the first example, extraction occurs because the resource is an input for production. The usage rate is a parameter in a fixed coefficient production function: one unit of the resource input allows manufacture of $\frac{1}{A}$ units of the product. In the second example, the product is a chemical which accumulates in the environment once it is used (e.g. agricultural chemicals in groundwater). The usage rate measures the propensity of the product to accumulate in the natural resource.[3] The second product is a backstop and does not use the

[3]There is no demand in the model for the usage rate of the product. This may seem surprising, since e.g. persistence would appear to be a desirable feature for many agricultural chemicals; it is the

natural resource.

Let the total stock of the resource at time t be $S(t)$, with an initial level S_0. The dynamics of the natural resource stock can be written as follows:

$$\frac{dS}{dt} = -Ax(t);$$

that is, the rate of change in the stock of the resource over time is equal to (minus) the level of production of the first product $x(t)$ multiplied by the usage rate A. To keep the analysis simple and to highlight the strategic behaviour involved, it is assumed that the resource is non-renewable and there is no uncertainty.

Environmental Regulation

Firms consider only the private value of the natural resource (the profits that can be made by sales of the resource-dependent product). But there may be social benefits – recreational, scientific or aesthetic – from the resource, beyond utility from consumption of the first product. To close the gap between social and private values, a social planner may decide to regulate use of the natural resource. This paper examines the effect of a quantitative restriction on the use of the resource.[4] The regulation considered takes the following form: sales of the first product are allowed while the resource stock stays above some critical level $\underline{S}$; should the stock fall below this limit, then the product is banned. (Since the resource is non-renewable, this is equivalent to a limit on total sales of the first product, for any given usage rate.) In order to isolate the incentives generated by environmental regulation, it is supposed that the

folklore reason for the popularity of DDT in the 1960s. There is, however, little empirical support for this assertion. Söderqvist (1996) and Beach and Carlson (1993), using hedonic price methods to analyse pesticide demand, both report that the coefficient on chemical persistence is statistically insignificant, and in any case has a negative sign.

[4]The effect of price-based regulation is considered elsewhere; see Mason (1997).

resource is sufficiently abundant that unregulated firms associate no Hotelling rents with its use. Any consideration by the firms of the resource stock is caused, therefore, by regulation; and any resulting strategic behaviour can be traced back directly to the requirement that $S(t) \geq \underline{S}\ \forall t$.

2.1. The Regulated Monopolist

A useful benchmark when assessing the effect of regulation will be the behaviour of a monopolist who does not face potential entry at t^*, but who is subject to regulation. Profit maximisation requires optimal choices of sales of the two products over time and the usage rate of the first product. The analysis initially will fix the usage rate at a constant A; section 2.3 will consider the optimal choice of A. The monopolist's problem is:

$$
\begin{aligned}
\max_{\{x(t),y(t),A\}} \quad & \int_0^\infty \mathrm{e}^{-rt} R(x(t)+y(t))dt \;-\; c\int_0^\infty \mathrm{e}^{-rt} y(t)dt, \\
\text{s.t.}\quad \dot{S}(t) &= -Ax(t), \\
S(0) &= S_0 \text{ (given)} \qquad S(t) \;\geq\; \underline{S}\ \forall t, \\
x(t), y(t) &\geq 0, \\
y(t) &= 0, \quad t < \tau,
\end{aligned}
$$

where $R = pD(Q)$ is the gross revenue of the monopolist. In words: the monopolist must choose sales of the two products x and y (and the usage rate A) to maximise the discounted sum of profits. The monopolist is constrained in her choices by the regulatory restriction that the first product is banned once the stock of the natural resource falls below the level $\underline{S}$; that product sales are non-negative; and that backstop is not available until τ.

The problem is a variant of one studied by Stiglitz and Dasgupta (1982); the next lemma follows directly from their proposition 2:

LEMMA 1: *The monopolist's optimal sales policy is:*

(i) if $(S_0 - \underline{S})$ is less than or equal to some critical level $S_M(\tau; A)$, then the first product is sold over the time period $t \in [0, \tau)$ so that marginal revenue rises at the rate of interest i.e. $\frac{\dot{MR}(t)}{MR(t)} = r$. The resource stock $(S_0 - \underline{S})$ is exhausted at time τ, at which time the first product is banned and sales of the backstop commence.

(ii) if $(S_0 - \underline{S}) > S_M(\tau; A)$, then the first product is sold during the period $t \in [0, T_M)$, where $T_M > \tau$, so that $\frac{\dot{MR}(t)}{MR(t)} = r$. At T_M, the resource stock is exhausted, the first product is banned, and sales of the backstop commence. T_M is defined by:

$$A \int_0^{T_M} D(p_M(t))dt = S_0 - \underline{S},$$

where p_M is the monopolist's price schedule (determined by $\frac{\dot{MR}(t)}{MR(t)} = r$) and $p_M(T_M) = \overline{p}$, the monopoly price of the backstop.

$S_M(\tau; A)$ is given by:

$$S_M(\tau; A) = A \int_0^{\tau} D(p_M(t))dt,$$

where $p_M(\tau) = \overline{p}$.

Figures 1 and 2 show possible paths for the monopolistic price schedule $p_M(t)$. In figure 1, the regulatory limit on resource use is low relative to the innovation date τ

$((S_0 - \underline{S}) < S_M)$. The non-availability of the backstop until τ and the assumption of an infinite choke-off price mean that the monopolist will not allow the resource stock to fall to $\underline{S}$ until τ. To ensure this, sales are kept low by setting a high price; indeed, the price of the first product exceeds the price $\overline{p}$ of its substitute at some time before τ. The regulatory limit is hit at $t = \tau$, at which time the first product is banned and the backstop brought onto the market. The price, having risen continuously over the period $t \in [0, \tau)$, falls discontinuously at τ to $\overline{p}$. In contrast, the regulatory limit is high $((S_0 - \underline{S}) > S_M)$ in figure 2. The monopolist is able to sell the first product for longer (and this is optimal since its cost is lower than the substitute's). The first product is sold until time $T_M > \tau$; at this time, the price of the first product (which has risen continuously before T_M) reaches the price of the substitute and the regulatory limit is reached.

Insert Figures 1 and 2

2.2. The Regulated Industry

The analysis now turns the optimal production policy of a regulated incumbent threatened with entry once the patent on the first product has expired. Following Stiglitz and Dasgupta (1982), the equilibrium derived is Stackelberg – this is the natural concept to use in a model in which one firm is dominant. It will be analytically convenient to suppose that the incumbent 'purchases' at t^* the remaining resource stock from the competitive industry, and then chooses her optimal production plan. Stackelberg equilibrium and the assumption of perfect forward markets[5] mean that,

[5] In the absence of such markets, problems of dynamic inconsistency arise. See Groot et al. (1996) for a treatment of this problem.

should other firms be in the market, the incumbent is constrained after t^* to set price such that $\frac{\dot{p}(t)}{p(t)} \leq r$ (see Stiglitz and Dasgupta (1982)). Finally, only open-loop strategies are considered; issues relating to sub-game perfection are ignored.

The incumbent's problem is:

$$\max_{\{x(t),y(t),A\}} \quad \int_0^\infty \mathrm{e}^{-rt} R(x(t)+y(t))dt \;-\; c\int_0^\infty \mathrm{e}^{-rt} y(t)dt \;-\; \mathcal{D}\mathrm{e}^{-rt^*} p(t^*)\left(S(t^*)-\underline{S}\right),$$

$$\begin{aligned}
\mathcal{D} &= 1 \quad \text{if } \; S(t^*) \;>\; \underline{S}, \\
&= 0 \quad \text{otherwise}, \\
\text{s.t.}\;\; \dot{S}(t) &= -Ax(t), \\
S(0) &= S_0 \text{ (given)}, \qquad S(t) \;\geq\; \underline{S} \;\; \forall t, \\
x(t), y(t) &\geq 0, \\
y(t) &= 0, \quad t < \tau, \\
\frac{\dot{p}(t)}{p(t)} &\leq r, \quad t > t^*, \text{ if } x(t) > 0.
\end{aligned}$$

(The third term in the maximisation problem corresponds to the present discounted cost to the incumbent of buying the resource stock at t^* from the industry.) The incumbent must choose sales x and y (and later the usage rate A) to maximise the discounted sum of profits, subject to the constraints that rivals may enter the market for the first product at t^*; the regulatory constraint that the first product is banned once the resource stock falls below the level $\underline{S}$; that sales be non-negative; and that the backstop is not available for sale until τ.

The incumbent's profit-maximising sales of the two products are given in the next lemma.

LEMMA 2: *The incumbent's optimal sales policy is:*

(i) if $t^* \geq T_M > \tau$ and $(S_0 - \underline{S}) > S_M(\tau; A)$, then the first product is sold during the period $t \in [0, T_M)$ so that $\frac{\dot{MR}(t)}{MR(t)} = r$. At T_M, the resource stock $(S_0 - \underline{S})$ is exhausted, the first product is banned, and sales of the backstop commence. There is no competitive phase in the sales of the first product.

(ii) if $t^* \geq \tau$ and $(S_0 - \underline{S}) \leq S_M(\tau; A)$, then the first product is sold during the period $t \in [0, \tau)$ so that $\frac{\dot{MR}(t)}{MR(t)} = r$, and the resource stock is exhausted at τ. At this time, the first product is banned and sales of the backstop commence. There is no competitive phase in the sales of the first product.

(iii) if $t^* \in [\tau, T_M)$ and $(S_0 - \underline{S}) > S_M(\tau; A)$, then sales of the first product over the period $t \in [0, t^*)$ are so that $\frac{\dot{MR}(t)}{MR(t)} = r$; over the period $t \in [t^*, T_2)$ so that $\frac{\dot{p}(t)}{p(t)} = r$ (where $p(T_2) = \overline{p}$, the monopoly price of the backstop). The resource stock $(S_0 - \underline{S})$ is exhausted at $T_1 \in (t^*, T_2)$, at which time sales of the backstop commence.

(iv) if $t^* < \tau$, then:

(a) if $(S_0 - \underline{S}) \leq \tilde{S}(t^*, \tau; A)$, then the first product is sold during the period $t \in [0, t^*)$ so that $\frac{\dot{MR}(t)}{MR(t)} = r$; over the period $t \in [t^*, \tau)$ sales are such that $\frac{\dot{p}(t)}{p(t)} = r$. The stock $(S_0 - \underline{S})$ is exhausted at τ, at which time sales of the backstop commence.

(b) if $(S_0 - \underline{S}) > \tilde{S}(t^*, \tau; A)$, sales of the first product are such that $\frac{\dot{MR}(t)}{MR(t)} = r$ during $t \in [0, t^*)$, and $\frac{\dot{p}(t)}{p(t)} = r$ during $t \in [t^*, T_4)$ (where $p(T_4) = \overline{p}$). The resource is exhausted at $T_3 \in (\tau, T_4)$, at which time sales of the backstop commence.

$\tilde{S}(t^*, \tau; A)$ *is defined by:*

$$\tilde{S}(t^*, \tau; A) = A \int_0^{t^*} D(p_M(t))dt + A \int_{t^*}^{\tau} D(\overline{p}e^{-r(\tau - t)})dt.$$

PROOF: See appendix.

The intuition behind the lemma's results is similar to that for lemma 1; indeed, parts (i) and (ii) of the lemma are identical. The other parts of the lemma are distinguished by how quickly the incumbent is able to exhaust the resource stock defined by the regulatory limit $\underline{S}$. In part (iv), case (a) of the lemma, the time to innovation is larger than the patent length and the regulatory limit is low. The incumbent is then able to ensure that the resource is exhausted (and hence competition restricted) as soon as the backstop is available for sale. Otherwise she must endure competition: until $T_2 > t^*$ (part (iii)) or $T_4 > \tau$ (part (iv), case (a)). Up until T_1 (respectively T_3), competition is direct (rivals are in the market for the first product); between T_1 and T_2 (T_3 and T_4), competition is indirect, with the incumbent committed to restraining the price of the backstop.[6] At T_2 (T_4), the incumbent once again becomes an unconstrained monopolist.

2.3. Regulation and Strategic Behaviour

Regulation of the natural resource raises the possibility of strategic behaviour by the incumbent. In the absence of regulation, other firms will enter the market at t^* and remain there in perpetuity. Environmental regulation ensures that these firms must eventually cease production, since sales of the first product are banned once

[6] She would like to set price equal to $\overline{p}$ immediately at T_1 (T_3); but she is constrained not to raise price at a rate greater than r.

the resource stock falls below $\underline{S}$. The incumbent can exploit this fact to restrict competition. Comparison of the optimal sales policies of the regulated monopolist (lemma 1) and the regulated incumbent faced with competition (lemma 2) allows a characterisation of the latter's strategic behaviour along familiar industrial economics lines.

PROPOSITION 1: *If*

(i) $t^* \geq T_M$, *or* $t^* \in [\tau, T_M)$ *and* $(S_0 - \underline{S}) \leq S_M(\tau; A)$, *then entry is blockaded;*

(ii) $t^* < \tau$ *and* $(S_0 - \underline{S}) \leq S_M(\tau; A)$, *then entry is 'accommodated';*

(iii) $t^* < T_M$ *and* $(S_0 - \underline{S}) > S_M(\tau; A)$, *then provided the resource stock* $(S_0 - \underline{S})$ *is not too large, entry is 'deterred'.*

PROOF: See appendix.

Entry 'accommodation' and 'deterrence' have specific meanings in the proposition. Entry accommodation occurs when the incumbent ensures that the regulatory limit is reached later than it would be if only the monopolist were operating in the market for the first product. (For example, when $t^* < \tau$ and $(S_0 - \underline{S})$ is greater than $\tilde{S}$ but smaller than S_M, the regulatory limit is hit at τ under the monopolist; but with rival producers, entry occurs at t^* and the limit is reached at $T_2 > \tau$. See the proof in the appendix.) Entry is deterred when, relative to the monopolist, the incumbent faced with potential competition ensures that the first product hits its regulatory limit early. (The proof of the proposition shows that, provided the initial stock $(S_0 - \underline{S})$ is greater than S_M but not too large, then if e.g. $\tau < t^* < T_M$, the limit is reached under the monopolistic regime at T_M, while when entry can occur, that level is reached at the earlier time T_1.)

Two competing factors balance to give proposition 1. Once entry occurs, the incumbent wants the first product to be banned as soon as possible, subject to the substitute being available, in order to limit competition. But the incumbent is constrained in reaching its objective to not raising price too quickly during competitive phases. The trade-off between the two factors determines when the regulatory limit is reached. In the entry accommodation case, the latter constraint is so binding that the limit is reached more slowly when entry occurs. In certain circumstances (case (iii) of the proposition), however, entry leads to increased resource use.

So far, the analysis has treated the usage rate as fixed. The next proposition investigates the optimal choices of A for various cases. The costs of choosing A are ignored to simplify the analysis; the importance of this simplification will be commented on below.

PROPOSITION 2: *The socially optimal usage rate is $\underline{A}$. The incumbent is indifferent to the value of the usage rate in the absence of regulation. The regulated monopolist's optimal usage rate is $\underline{A}$. The regulated incumbent's optimal usage rate is strictly greater than zero. For low enough $\underline{A}$, her optimal A will be greater than the social planner's; and under certain circumstances it may take the maximum value of 1.*

PROOF: See appendix.

There is a sharp contrast between the four cases considered. The social planner will choose to manufacture products which have minimal resource dependence. The unregulated monopolist makes the same choice.[7] The regulated incumbent does not care what value A takes. But a firm subject to regulation who holds one patent and expects to win another in the future, will certainly choose a non-zero usage rate; and may (for certain parameter values of the model) manufacture products that have the maximum extent of resource dependence.[8] Note that it is not certain from the proposition that the usage rate will rise as a consequence of regulation. There are two reasons for this. First, the indifference of the unregulated incumbent means that she may choose a usage rate which exceeds the regulated incumbent's optimal A. Secondly, if $\underline{A}$ is high, then the regulated incumbent's optimal choice will be $\underline{A}$.[9] But the proposition offers an explanation for why regulation *might* cause an increase in the usage rate of a resource-dependent product.

Clearly, the corner solutions for A are a consequence of the assumption that the choice of A is costless. This assumption has been made to avoid making any assumptions about these costs, about which little is known. The spread in optimal choices of A identified in proposition 2 derives from the shape of the value functions, gross of any costs of choosing A. The differences in the optimal usage rates are likely

[7] $A = \underline{A}$ is also the optimal choice for a firm which holds the patent on the first product but does not anticipate winning future patents.

[8] For example, one set of parameter values that ensures that the optimal A for the incumbent equals 1 is as follows:

$$\begin{aligned} t^* &> \tau, \\ S_0 - \underline{S} &> \int_0^{t^*} D(p_M(t))dt, \end{aligned}$$

where p_M is the price schedule that results from marginal revenue rising at the proportional rate r and $p_M(t^*) = \overline{p}$.

[9] Figures 5 and 6, described in the appendix, show the regulated incumbent's value function against the effective resource stock $S = \frac{(S_0 - \underline{S})}{A}$. The value function reaches a maximum at some finite S i.e. at a usage rate greater than zero. But if $\underline{A}$ is sufficiently large, then there is an upper bound on the effective stock: $S \leq \frac{(S_0 - \underline{S})}{\underline{A}}$. This bound may lie to the left of the maximum in the value function; and so the optimal usage rate is $\underline{A}$.

to remain, therefore, whatever the nature of costs.

3. Case Study: The Italian Herbicide Industry

This section presents a case study of the agricultural chemical industry to assess the empirical support for the model predictions. In July 1980, the European Commission issued a directive (Number 80/778/EEC), setting a maximum admissible concentration (MAC) for individual pesticides in drinking water of 0.1 μg/l, and a 'cocktail' standard of 0.5 μg/l for the total concentration of all pesticides. States failing to meet the conditions of the Directive risk condemnation by the European Court of Justice, and imposition of penalty payments (see Faure (1994)). For example, in Italy, concentrations of atrazine, a herbicide used in maize cultivation, reached this level in 1984; in 1989, eleven wells in the Veneto region recorded atrazine levels of over 1 μg/l (see Zanin et al. (1991)). Local restrictions in 1986 against contaminated drinking water supplies had little effect, and a nationwide ban on the sale and use of atrazine was imposed in 1990.[10]

The model developed in section 2 may be a reasonable description of the European agrochemical sector. The market structure of the industry conforms to the model set-up: very few firms engage in research and development (so that a current patent holder is very likely to win patents in the future); and there is a large number of imitating firms (so that competition after a patent expires is perfect).[11] The regulatory

[10]Atrazine was not the only chemical to be banned: the sale and use of alachlor on soya was also prohibited. In addition, maximum permissible doses of several chemicals were reduced significantly. See Zanin et al. (1991).

[11]Twelve firms account for around 80% of the world agrochemical market. Only these large firms are involved in research and development to any significant degree. Current regulation mandates the release of the full dossier of data for any out-of-patent chemical to any firm that can manufacture a

approach used in the atrazine case is equivalent to the form of regulation analysed in the previous section. The MAC effectively mandates that the stock of the natural resource must not fall below $\underline{S}$; the ban on atrazine removes from use the offending product once the effective stock $(S_0 - \underline{S})$ is exhausted.

What evidence is there that chemical manufacturers have responded to the MAC regulation in the way predicted by the model in the previous section? Propositions 1 and 2 suggest that production may be distorted as firms behave strategically; the distortion involves both output and the usage rate – accumulation characteristics – of the products sold. The first proposition cannot be tested, since sales data are not available (to keep market shares secret). There is qualitative data, however, to test the second proposition.

Figure 3 (taken from Vighi and Zanin (1994)) shows GUS indices for 14 herbicides.

Insert Figure 3

The GUS index indicates the ability of an agricultural chemical to accumulate in groundwater, and has two components. The water solubility of a chemical is measured by its partition coefficient K_{OC}.[12] The higher the coefficient, the less soluble is the chemical in water. Degradability of the chemical is measured by the (logarithm of the) half-life in soil $(t_{1/2})$. The GUS index is then defined by $\text{Gus} = \log t_{1/2}(4 - \log K_{OC})$; herbicides are classified as water leachers (Gus > 2.8), non-leachers (Gus < 1.8), or

similar product. (There is, of course, some controversy about what constitutes a 'similar' product.) There were approximately ninety agrochemical firms engaged in the manufacture of previously-patented products in the European Union in 1994. See Nadai (1995).

[12] K_{OC} measures the relative solubility of non-ionic molecules in an organic medium (octinel) versus water. It indicates the extent to which a chemical binds to soil: a high K_{OC} means a strong binding tendency, and therefore a low water solubility.

transitional ($1.8 \leq \text{Gus} \leq 2.8$).

Chemicals labelled with numbers are herbicides used in Italy before the banning of atrazine (labelled '1' in the figure). Immediately striking is the clustering of all but three of these chemicals at moderate solubilities and half-lives, and hence with transitional to leaching values of the GUS index. The chemicals labelled with letters are three herbicides that have been registered for use in Italy after the imposition of the ban on atrazine. The GUS indices of two of these products are greater than those of the previous substitutes for atrazine (linuron and terbutylazine, labelled '7' and '11' respectively); the GUS index of the third is comparable to previous levels. Figure 3 shows, therefore, that the result of the atrazine ban has been an increase in the accumulation ability of chemicals.

The expected effect of MAC regulation is a decrease in chemicals' accumulation abilities. The theory developed in this paper offers some explanation for the rise in the GUS indices of herbicides in Italy after MAC regulation was introduced. This is obviously not a conclusive test of proposition 2. The evidence does suggest, however, that firms are not reacting in a simple fashion to the regulation introduced in Italy.

4. Conclusions

This paper has examined the opportunities for strategic behaviour that can be created by environmental regulation. The model analysed the choices of an incumbent holding two patents, the first on a product available immediately for sale, the second on a more expensive substitute available in the future. The incumbent chooses sales of the two products, and also the degree to which the first product uses a natural resource in its manufacture and sales. The incumbent faces the possibility of entry to the market for the first product; the industry is regulated so that the product is banned once the resource stock falls below some critical level. The paper showed that the incumbent may react to regulation by driving the resource stock down to the regulatory limit so that the first product is banned. The incumbent achieves this in two ways: first, by increasing sales of the product; secondly, by choosing to manufacture products which use the resource to a socially excessive extent. Entry deterrence protects profits from sales of the second patented product.

Product bans, by sending out a clear message as to which products and technologies are socially acceptable and which are not, seem a sensible way for regulators to attack the problem of over-exploitation of natural resources. This ignores, however, the opportunities that may be created for entry deterring behaviour. The imposition of a regulatory limit on resource extraction defines a capital stock that manufacturers can use strategically; the anticipation of a future patent gives the incentives to do so. This gives rise to the perverse outcome that the efforts of regulators may only exacerbate the problem of excessive resource use.

APPENDIX

Proof of Lemma 2.

Parts (i) and (ii) of the lemma follow from lemma 1. Proof of the other parts is straightforward, and uses the arguments in Stiglitz and Dasgupta (1982). Only one point requires further exposition: that in parts (iii) and (iv), $T_1 < T_2$ and $T_3 < T_4$. It will be shown here how to adapt the proof in appendix A of Stiglitz and Dasgupta when the price elasticity of demand is a constant ϵ for part (iii). (Extension to the case where $\epsilon'(Q) > 0$ follows easily; the proof for part (iv) is similar.) Constant elasticity of demand means that $\frac{\dot{p}(t)}{p(t)} = r$ during $t \in [0, T_2)$. Then the incumbent's problem is:

$$\begin{aligned}
\max \qquad & \int_0^{T_2} \mathrm{e}^{-rt} p(0) D(p(0)\mathrm{e}^{rt})dt \; - \; c\int_{T_1}^{T_2} \mathrm{e}^{-rt} D(p(0)\mathrm{e}^{rt})dt \; + \; \mathrm{e}^{-rT_2}\overline{\pi} \\
& - p(0)\left(S(t^*) - \underline{S}\right),
\end{aligned}$$

$$\text{s.t. } A\int_0^{T_1} D(p(0)\mathrm{e}^{rt})dt \; = \; S_0 - \underline{S}, \tag{A1}$$

$$p(0)e^{rT_2} \; = \; \overline{p},$$

$$S(t^*) \; = \; S_0 - A\int_0^{t^*} D(p(0)\mathrm{e}^{rt})dt, \tag{A2}$$

where $\overline{\pi}$ is the present discounted value of monopoly profits from sales of the backstop after T_2. Differentiating the regulatory constraint (A1):

$$p(0)\frac{dT_1}{dp(0)} = \frac{\epsilon\int_0^{T_1} D(p(t))dt}{D(p(T_1))}.$$

Differentiation of equation (A2) gives:

$$p(0)\frac{dS(t^*)}{dp(0)} = A\epsilon\int_0^{t^*} D(p(t))dt.$$

Using these two expressions gives:

$$\frac{\partial V}{\partial p(0)} \;=\; -\int_0^{T_1} \epsilon D\left[1 - \frac{c}{p(0)\mathrm{e}^{rT_1}}\right]dt + \int_{T_1}^{T_2} D\left[1 - \epsilon\left(1 - \frac{c}{p(0)\mathrm{e}^{rt}}\right)\right]dt - A\int_0^{t^*} D(\epsilon - 1)dt.$$

Suppose that the patent holder chooses $p(0)$ so that $T_1 = T_2$. Then:

$$\left.\frac{\partial V}{\partial p(0)}\right|_{T_1=T_2} = -\epsilon\left[1 - \frac{c}{p_0 \mathrm{e}^{rT_1}}\right]\int_0^{T_1} Ddt - A(\epsilon - 1)\int_0^{t_*} Ddt.$$

When $T_1 = T_2$, $p(0)\mathrm{e}^{rT_1} = \overline{p} > c$; and $\epsilon > 1$. Therefore $\left.\frac{\partial V}{\partial p(0)}\right|_{T_1=T_2}$ is negative, and so the incumbent will choose a lower $p(0)$ than would be required for $T_1 = T_2$. Consequently sales of the first product increase, and the resource is exhausted more quickly i.e. $T_1 < T_2$. □

Proof of Proposition 1.

Part (i) of the proposition (blockaded entry) is direct: it follows from lemma 1 and part (i) of lemma 2 (in this case, the sales policy of the monopolist and the incumbent threatened with entry are identical).

In part (ii) of the proposition (entry accommodation), $t^* < \tau$ and $(S_0 - \underline{S}) \leq S_M$. In this case, the regulatory limit is reached at τ under monopoly and at τ (if $(S_0 - \underline{S}) \leq \tilde{S}$) or $T_2 > \tau$ (if $(S_0 - \underline{S}) \in (\tilde{S}, S_M]$) under the incumbent threatened with entry. Two parts of the above statement require proof: first that $\tilde{S} < S_M$; secondly, that $T_2 > \tau$. The following definitions are given in lemmas 1 and 2:

$$\begin{aligned} S_M(\tau; A) &= A\int_0^{\tau} D(p_M(t))dt, \qquad p_M(\tau) \ = \ \overline{p}, \\ \tilde{S}(t^*, \tau; A) &= A\int_0^{t^*} D(p_M(t))dt + A\int_{t^*}^{\tau} D(\overline{p}\mathrm{e}^{-r(\tau-t)})dt. \end{aligned}$$

As noted above, price rises at a (weakly) slower rate during the competitive phase than under a monopoly. It must be, therefore, that the price schedule of the monopolist lies entirely below the price schedule of the incumbent/competitive market structure. Hence, from the definitions, $S_M > \tilde{S}$. Secondly, the assumption of an infinite choke-off price ensures that T_2 must be greater than or equal to τ.

In part (iii) of the proposition (entry deterrence), $t^* \in [\tau, T_M)$ or $t^* < \tau$ and $(S_0 - \underline{S}) > S_M$. In these cases, the regulatory limit is reached at T_M under monopoly and at T_1 or T_3 under the entry-threatened incumbent. The conditions for entry deterrence will be shown for the first of the two cases; the proof is similar for the other case. So the conditions under which $T_1 < T_M$ must be shown. T_1 and T_M are defined by:

$$\begin{aligned} A\int_0^{t^*} D(p_M(t))dt + A\int_{t^*}^{T_1} \overline{p}e^{-r(T_2-t)}dt &= S_0 - \underline{S}, \\ A\int_0^{T_M} D(p_M(t))dt &= S_0 - \underline{S}, \qquad p_M(T_M) = \overline{p}. \end{aligned}$$

A simple graph of the price schedules under the two regimes indicates that $p_P(t^*)$ cannot be too much larger than $p_M(t^*)$ (otherwise the monopolistic price schedule will lie everywhere below the incumbent's price schedule, and so $T_M < T_1$ – contrary to what is wanted). It will be shown that this implies that the initial stock $(S_0 - \underline{S})$ cannot be too large. Consider the period $t \in (t^*, T_1)$. From proposition 2c of Stiglitz and Dasgupta (1982):

$$\frac{dp_M}{dS} \leq \frac{dp_P}{dS} \leq 0$$

during this period for $\epsilon'(Q) \geq 0$. Further, $p_M(T_1) = \overline{p}$ while $p_P(T_1) < \overline{p}$. Figure 4 plots the price schedules against the stock remaining at t^* for the case $\epsilon'(Q) > 0$.

Insert Figure 4

It is clear from the figure that the requirement that $p_P(t^*)$ not be much larger than $p_M(t^*)$ means that the stock remaining to the incumbent at t^* cannot be too large: $S(t^*) < \check{S}$ for some $\check{S}$. In turn, this implies that the initial stock cannot be greater than some level S^*.

The last part of the proof is to show that part (iii) of the proposition can occur i.e. that $S^* \geq S_M$. An example of such a case will be given here; by continuity, other examples (perhaps very close in parameter values to the one given) must exist. Suppose $t^* = 0$ and $\epsilon'(Q) = 0$ (zero patent duration on the first product and isoelastic demand). The proof of lemma 2 noted that the incumbent will choose $p(0)$ so that $T_1 < T_2$; this was shown by determining that $\left.\frac{\partial V}{\partial p(0)}\right|_{T_1=T_2} < 0$. The value of $p(0)$ which sets $T_1 = T_2$, when $t^* = 0$ and $\epsilon'(Q) = 0$, is $p_M(0)$ (the initial price chosen by the perpetual monopolist). Therefore $p(0) < p_M(0)$, and so $T_1 < T_M$ when $(S_0 - \underline{S}) > S_M$. There is, therefore, at least one case in which entry deterrence can occur (in this case, $S^* = \infty$). $\square$

Proof of Proposition 2.

The initial resource stock available for use by the regulated industry is $(S_0 - \underline{S})$. A higher A is equivalent to a lower effective initial stock:

$$\begin{aligned} S_0 - \underline{S} &= A\int_0^\infty x(t)dt \\ \Rightarrow \quad \frac{(S_0 - \underline{S})}{A} &= (S_0' - \underline{S}') \quad = \quad \int_0^\infty x(t)dt, \end{aligned}$$

where $(S_0' - \underline{S}') \geq (S_0 - \underline{S})$. The effective stock $(S_0' - \underline{S}')$ is decreasing in A. The proposition deals with the derivative of value functions with respect to the usage rate A; but from the above, this is related to (minus) the derivative of the value functions with respect to the initial resource stock $(S_0 - \underline{S})$. This will prove useful, since it means that standard results about continuity of value functions with respect to the initial level of the state variable(s) (see, for example, Stokey and Lucas, theorem 4.11, p. 85) can be employed.

It is straightforward that the social optimum requires $A = \underline{A}$ – this value protects the resource and delays use of the more expensive backstop to the maximum extent.

Since no regulation is imposed on the industry and the resource stock is assumed to be abundant, the unregulated incumbent will not consider the resource stock in her profit maximisation decision. Demand, by assumption, does not depend on A. The usage rate does not appear, therefore, in the maximised value function of the unregulated incumbent. So the unregulated incumbent is indifferent to the value of A.

Let V_M be the maximised value function of the regulated monopolist. Then:

$$\frac{\partial V_M}{\partial (S_0 - \underline{S})} = \mu(0) > 0,$$

where $\mu(0)$ is the value of the co-state variable attached to the constraint $\dot{S} = -Ax$ at time $t = 0$. Since the derivative of the value function is positive, the optimal usage rate of the monopolist is the lowest possible value, $\underline{A}$.

Let V_I be the maximised value function of the regulated incumbent. Figures 5 and 6 plot V_I against the effective initial stock $S = \frac{S_0 - \underline{S}}{A}$; $t^* > \tau$ in figure 5 and $t^* \leq \tau$ in figure 6. Figure 5 has three regions, according to which of the cases in lemma 2 holds. When S is low (greater than $(S_0 - \underline{S})$ but less than $S_1 = \int_0^\tau D(p_M(t))dt$, where p_M is the monopolistic price schedule and $p_M(\tau) = \overline{p}$), then case (ii) holds. For S between S_1

and $S_2 = \int_0^{t^*} D(p_M(t))dt$, where $p_M(t^*) = \overline{p}$, case (i) holds. For S greater than S_2, case (iii) holds. (It is straightforward to show that this is the only case that can occur when $t^* > \tau$.) From lemma 2, it is clear that the incumbent's value function is increasing in the effective resource stock S in cases (i) and (ii). In both cases, no entry occurs (since the stock is exhausted before t^*), and therefore profits must increase as the resource constraint is relaxed. So in figure 5, $V_I(S)$ is strictly increasing in S for $S \leq S_2$. Consider $S > S_2$. By continuity of the value function with respect to the initial stock (see Stokey and Lucas), V_I must be upward sloping in a neighbourhood of $S = S_2$. V_I must be decreasing in S, however, for sufficiently large S. To see this, consider the limiting value $A = 0$ i.e. $S = \infty$. In this case, the resource stock is never exhausted and competition is perpetual once entry occurs. But for an arbitrarily small increase in A, there is only a second-order direct effect in the incumbent's profits; but there is a first-order indirect increase resulting from the eventual exit of rivals from the industry. Therefore $V(S)$ must be downward sloping for large enough S. By continuity, there must be a maximum value of $V(S)$, corresponding to a usage rate A greater than zero but less than $A_2 = \frac{S_0 - \underline{S}}{\int_0^{t^*} D(p_M(t))dt}$. Notice that A_2 may be greater than 1, so it is possible that the regulated incumbent's optimal value of the usage rate is the maximum value of 1.

A similar logic operates in figure 6, which has two regions, separated by the value $S = S_3 = \int_0^{t^*} D(p_M(t))dt + \int_{t^*}^{\tau} D(\overline{p}e^{-r(\tau - t)})dt$. To the left, case (iv, a) of lemma 2 holds; to the right, case (iv, b). $V_I(S)$ must be increasing when $S < S_3$. Using the same argument as above, V_I reaches a maximum at some $S > S_3$, corresponding to a value of the usage rate which is greater than zero but less than $A_3 = \frac{S_0 - \underline{S}}{S_3}$. Again, A_3 may be greater than 1, so the incumbent's optimal A may be the maximum value of 1.

Insert Figures 5 and 6

Finally, consider the case of a firm which has an initial patent, but will not hold a patent in the future. If the future patent is held by another single firm, then clearly the initial incumbent will set $A = \underline{A}$, since there will be no benefit to it of closing the market for its product earlier than necessary. (The same conclusion holds if there is no future patent, so that the backstop can be sold competitively by the entire industry. This can be seen from the derivative of the maximised value function V' of the incumbent:

$$\frac{\partial V'}{\partial(S_0 - \underline{S})} = \mu(0) > 0,$$

where $\mu(0)$ is again a co-state variable value at $t = 0$.) $\square$

REFERENCES

Beach, E. D. and G. A. Carlson, (1993): "A Hedonic Analysis of Herbicides: Do User Safety and Water Quality Matter?", *American Journal of Agricultural Economics*, 75(3), 612–23.

Bergman, L. and D. M. Pugh (eds.), (1994): *Environmental Toxicology, Economics and Institutions: The Atrazine Case Study*, Kluwer Academic Publishing.

Dasgupta, P., (1981): "Resource Pricing and Technological Innovations under Oligopoly: A Theoretical Exploration", *Scandinavian Journal of Economics*, 83(2), 289–317.

Dasgupta, P., R. J. Gilbert and J. E. Stiglitz, (1982): "Invention and Innovation under Alternative Market Structures: The Case of Natural Resources", *Review of Economic Studies*, 49(4), 567–82.

Dasgupta, P., R. J. Gilbert and J. E. Stiglitz, (1983): "Strategic Considerations in Invention and Innovation: The Case of Natural Resources", *Econometrica*, 51(5), 1439–48.

Dasgupta, P. and J. E. Stiglitz, (1981): "Resource Depletion under Technological Uncertainty", *Econometrica*, 49(1), 85–104.

Dixit, A., (1980): "The Role of Investment in Entry-Deterrence", *Economic Journal*, 90(357), 95–106.

Faure, M., (1994): "The E.C. Directive on Drinking Water: Institutional Aspects", in Bergman, L. and D. M. Pugh (eds.), *Environmental Toxicology, Economics and Institutions*, Kluwer, 39–87.

Fioretti, C. S., G. Zanin, P. Ferrario and M. Vighi, (1995): "Weed Control on Maize in Italy: Agronomic and Environmental Inputs for an Economic Analysis", Draft chapter for Swanson, T. M. and M. Vighi (eds.), *The Regulation of Persistent Chemicals: Economics, Institutions and Environmental Toxicology*, Cambridge University Press, 1997 (forthcoming).

Gilbert, R. J., (1989): "Mobility Barriers and the Value of Incumbency", in Schmalensee, R. and R. Willig (eds.), *Handbook of Industrial Organisation*, North Holland, Amsterdam.

Gilbert, R. J. and D. M. G. Newbery, (1982): "Preemptive Patenting and the Persistence of Monopoly", *American Economic Review*, 72(3), 514–526.

Groot, F., C. A. A. M. Withagen and A. de Zeeuw, (1996): "Strong Time-consistency in the Cartel-versus-fringe Model", *C*OSOR Working paper 96-04, Eindhoven University of Technology.

Klemperer, P. D., (1987): "Entry Deterrence in Markets with Consumer Switching Costs", *Economic Journal*, 97(0), Supplement, 99–117.

Klemperer, P. D., (1989): "Price Wars Caused by Switching Costs", *Review of Economic Studies*, 56(3), 405–20.

Mason, C. F. and S. Polasky, (1994): "Entry Deterrence and the Commons", *International Economic Review*, 35(2), 507–525.

Mason, R. A., (1997): "Cost Raising Strategies in a Symmetric, Dynamic Duopoly", Mimeo, Nuffield College.

Mookherjee, D., and D. Ray, (1986): "Dynamic Price Games With Learning-by-Doing", *Stanford Graduate School of Business Research Paper*, No. 884.

Nadai, A., (1995): "The E.U. Regulatory Process in Pesticide Registration", *CERNA Working Paper.*

Rölike, A., (1996): "The Ban of a Single Pesticide", *Geneva Papers on Risk and Insurance*, 21, 224–239.

Söderqvist, T., (1996): "Herbicide Characteristics, Implicit Prices, and the Prediction of Herbicide Use: The Case of Maize Cultivation in Italy", in Swanson, T. M. and M. Vighi (eds.), *The Regulation of Persistent Chemicals: Economics, Institutions and Environmental Toxicology*, Kluwer Academic Press, (forthcoming).

Stiglitz, J. E. and P. Dasgupta, (1981): "Market Structure and Resource Extraction under Uncertainty", *Scandinavian Journal of Economics*, 83(2), 318–33.

Stiglitz, J. E. and P. Dasgupta, (1982): "Market Structure and Resource Depletion: A Contribution to the Theory of Intertemporal Monopolistic Competition", *Journal of Economic Theory*, 28, 128–164.

Stokey, N. L. and R. E. Lucas, Jnr., (1989): *Recursive Methods in Economic Dynamics*, Harvard University Press.

Vighi, M. and G. Zanin, (1994): "Agronomic and Ecotoxicological Aspects of Herbicide Contamination of Groundwater in Italy", in Bergman, L. and D. M. Pugh (eds.), *Environmental Toxicology, Economics and Institutions*, Kluwer, 111–139.

Zanin, G., M. Borin, L. Altissimo and D. Calamari, (1991): "Simulazione della contaminazione da erbicidi nell'acquifero a Nord di Vicenza Italia nord-orientale", Paper presented at the 25th Annual Meeting of SIA, Bologna.