International Consortium on
Agricultural Biotechnology Research (ICABR)

8th ICABR International Conference
on

*Agricultural Biotechnology:
International Trade and
Domestic Production*

Ravello (Italy), July 8 - 11, 2004

Do Monopoly Rights Promote Conservation?

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Abstract. This paper explores the problem of sequential exploitation of exhaustible resources by a monopolist, when a setup cost must be incurred to access the next pool. Under certain circumstances, the monopolist will always follow a more conservationist path of extraction and delay the introduction of new resource pools compared to a social planner. However, with other forms of consumer demand, the monopolist may exhaust the resource more quickly, especially if many new options will follow. These results may apply especially to depletable resources like antibiotics or biotech products, for which significant research and development costs are required, followed by monopoly rights conferred by patents.

JEL Classification No(s).: Q3, C62

Keywords. natural resources, setup costs, invention, monopoly, economics of resistance

1 Introduction

The question of whether an exhaustible natural resource will be extracted at a socially optimal rate under imperfect competition, which first arose in the context of OPEC cartels in the 1970s, has reemerged in recent years in the context of new kinds of resources, such as antibiotics and crops genetically engineered to repel pests. Pesticides and antibiotics can be thought of as depletable resources, due to the selective pressure they place on susceptible bacteria or pests, which ensures that they become less effective with use (Laxminarayan and Brown, 2001). The problems of sub-optimally high rates of depletion that are associated with the open access nature of these resources are ameliorated to some extent by the existence of the patenting system. Although patents on antibiotics and pesticides are intended to reward innovators for undertaking the investment that leads to the innovation, they serve an additional purpose in the context of resistance-prone resources in that they give the patent holder an incentive to care about the rate at which resistance develops. Some have argued, therefore, that giving innovators longer patents would increase their incentives to internalize the problem of emergence of resistance (OTA report, Stephen Brown). Others have extended this argument to claim that the existence of patents relieves society from the burden of regulating for resistance since the patentee may have sufficient incentives to consider the depletion of product effectiveness. An additional feature of patents is that they often (though not always) give the patentee a head start in developing future drugs and pesticides that depend on the basic patent. This paper examines the issue of monopoly provision of a depletable resource when the patentee has the option of developing future resource pools after incurring some setup cost. It demonstrates that granting patents to firms may not necessarily give them a stronger incentive to protect their product from resistance.

A number of authors have written on the implications of monopoly for the extraction of an exhaustible resource: Weinstein and Zeckhauser (1975), Stiglitz (1976), Kay and Mirrlees (1975), Lewis (1976), Stiglitz (1976), Sweeney (1977), Dasgupta and Heal (1979), Tullock (1979), Lewis et al. (1979), Eswaran and Lewis (1984), Pindyk (1987), and Gaudet and Lasserre (1988), among others. Reviews of this literature are included in Peterson and Fisher (1977), Dasgupta and Heal

(1979), Devarajan and Fisher (1981), and Krautkraemer (1998). However, the role of future pools of resources and the associated setup costs in monopoly provision has received relatively little attention in these papers. Many traditional natural resources (and non-traditional ones like antibiotics and pesticides that are the focus of this paper) involve significant setup costs—fixed costs of exploration and development that must be incurred before any extraction can begin. Major investments in research and development, as well as the approval process, must occur before the products can be brought to market.

Hartwick, Kemp and Long (1986) showed that in the presence of setup costs the social optimum dictates sequential exploitation of the natural resource pools, and the optimal path of marginal current net benefit will rise in a "saw-tooth" fashion. While any particular pool is being expoited, the marginal net benefit rises at the rate of interest, dropping down when a switch is made to the next pool, with the difference reflecting the marginal benefit of postponing the switch. Since setup costs create a nonconvexity, they indicated and Fischer (forthcoming) proves that the socially optimal path cannot then be decentralized to a perfectly competitive equilibrium. Thus, the true extraction path would be characterized by some form of imperfectly competitive equilibrium. This paper analyzes the exploitation path that would occur with monopoly ownership of the resource pools and compares it to the planner's problem.

Dasgupta, Gilbert and Stiglitz (1982) considered setup costs in the form of the cost of inventing a new technology. With that technology functioning as a backstop substitute for the existing resource, the monopolist is shown to prolong extraction and delay implementation of the new technology compared to the planner. However, this result cannot be generalized when the setup investment produces the next in a sequence of exhaustible resources. The important difference is that with a non-exhaustible backstop, marginal costs are the same for the planner and the monopolist; thus, the relative stream of value from the new technology depends on consumer surplus and total revenue, given the same costs. However, when the new technology is also exhaustible, the marginal costs incorporate a scarcity value—and that scarcity value is different for the monopolist and the planner. Furthermore, the scarcity values also depend on how many more new technologies or resource pools remain in the sequence. Therefore, the planner and the monopolist face different kinds of tradeoffs in deciding when to exhaust the current resource and move on to the next, and those relative incentives depend further on the structure of demand and the availability of future sources.

In this paper, we describe how these issues arise with new importance in application to problems of resistance, with the example of Bt crops and antibiotics (Section 2). We then present a model to analyze the general problem of sequential exploitation for both the planner and the monopolist (Section 3). Under certain circumstances, the monopolist will always follow a more conservationist path of extraction and delay the introduction of new resource pools compared to a social planner. However, if consumer demand takes other forms, the monopolist may exhaust the resource more quickly, especially if many new options will follow. This result is demonstrated using a slight variation on the model in Stiglitz (1976), which features constant elasticity of demand with zero extraction costs. In that case, without setup costs, the monopolist extracts at the same rate as the social planner. We find that in the presence of setup costs the monopolist is either more or less conservative than the social planner, depending on how many resource pools remain. If few resource pools are available after the current one is exhausted, the monopolist behaves more conservatively than the planner, extracting more slowly and delaying the setup of the next pool. However, if many resource pools remain in the queue, the monopolist extracts faster than the planner, more impatient to access the future revenue stream.

2 Background

The theoretical questions addressed in this paper shed light on the policy debate over the extent to which a new generation of genetically modified crops should be regulated for pest resistance. Recent efforts to deal with pest infestations in agriculture have been bolstered by the availability of commercial crops engineered to express the Bt protein. These proteins, which were first isolated from a soil microbe *Bacillus thuringiensis* (hence the abbreviation, Bt), have been found to be highly effective in killing lepidopterans, including the tobacco budworm (*Heliothis virescens*), cotton bollworm, (*Helicoverpa zea*) and the European corn borer (*Ostrinia nubilalis*), while being apparently harmless to other species, including humans.

Although Bt has been used in foliar sprays for over four decades, mostly in organic farming, there is no known pest resistance to Bt proteins. However, with rapidly expanding acreage of crops planted that express the Bt gene and resulting widespread exposure of pests to the Bt toxin from commercial agriculture, as well as the fact that the current generation of transgenic crops express only a single toxin – the Bt *Cry1Ac* (cotton) or *Cry1Ab* (corn)[1] – it is commonly believed that is only a matter of time before resistance to Bt crops is detected. In anticipation of this eventuality, Monsanto, the primary manufacturer of Bt transgenic crops, has already developed the next generation of transgenics that contain both the old *Cry1Ac* gene and the new *Cry X* gene and offer greater resiliency against the development of resistance. It is common knowledge in the industry that future generations of pest resistant crops based on Bt toxins are already under development.[2] It is reported that developing of a genetically modified Bt plant variety can take 6 to 12 years and cost between $50 million and $300 million.[3]

Recognizing the societal benefits of conserving the effectiveness of the Bt technology, the United States Environmental Protection Agency (USEPA) requires seed companies to ensure that farmers plant a certain proportion of their fields with a non-Bt variety.[4] The justification for this regulation is that the refuge strategy would allow for interbreeding between pests which may have developed resistance to Bt, and pests surviving on non-Bt crop that are susceptible to Bt. Additionally, the strategy calls for expressing a level of Bt toxin in the crop that is over 25 times the toxic concentration required to kill susceptible larvae. Similar regulations have been imposed in Canada

[1] The prefix *Cry* refers to the fact that the endotoxins normally exist in crystalline form.

[2] Many variants of Bt toxins found in nature and it is theoretically possible to produce a large number of future generations of Bt crops. This possibility is not as utopian as it seems, however. Some researchers have found that a single gene can confer resistance to four Bt toxins – therefore some undiscovered Bt toxins may be doomed already. Tabashnik B, "Seeking the root of insect resistance to transgenic plants" PNAS 94: 3488-90, 1997.

[3] High industry concentration – Study: Bio-food research increasingly concentrated. Feb 20, 2003, Reuters.

[4] In fact, EPA regulations regarding GMOs are the first from any agency in the United States that treat pest susceptibility as a public good (Livingston et al. 2000), even though resistance issues arose with more traditional pesticides as well.

under the Seeds Act and Part V of the Seeds Regulations administered by the Canadian Food Inspection Agency (CFIA). These regulations also require (in the case of Bt corn, for instance) that non-Bt corn be planted within 1/4 mile of the farthest Bt corn in a field to provide a refuge where Bt-susceptible pests may exist. There are strict penalties for non-compliance including a withdrawal of permission to grow the crop for two years.

The last five years have been witness to a contentious debate over the question of the optimal refuge size and whether current refuge requirements are socially optimal (Georghiou 1981; Gould 1988; Tabashnik 1994; Hurley, Secchi et al. 1999; Hyde, Martin et al. 1999; Sloderbeck, Buschman et al. 2000; Secchi and Babcock 2002). While industry and farmer groups have argued for smaller non-Bt refugia than the currently mandated 20%, environmental groups are fighting for refuge requirements as large as 50% of cultivated acreage. Some economists, however, have gone as far as to speculate whether these refuge regulations are required at all (Noonan 2002). After all, since Monsanto is a monopolistic owner of the Bt technology[5], it may have a greater incentive for ensuring that growers are scrupulous in planting refuges than would be the case if genetically modified Bt seeds were competitively supplied. Under certain conditions, this incentive may be large enough to ensure an even greater level of effort to enforce a resistance management policy than is socially optimal. In other words, one would expect to see refuges being grown even if EPA did not mandate them, because although EPA may care about the cost of growing refuges, the seed company ignores this cost as long as the farmer is able to grow a profitable crop. Even if one were not to go so far as to advocate no regulation for pest resistance at all, it is important to understand the incentives that Monsanto faces with respect to the effectiveness of the current Bt technology given that it has a number of potential backstop technologies waiting in the pipeline. One could argue for comparatively less regulatory stringency if Monsanto has sufficient incentives to "care" about resistance to its products.

[5]Monsanto does not have a monopoly on Bt foliar sprays, however. Still, this does not affect our assumption that Monsanto has a monopoly on Bt. Bt foliar sprays have been around for a long time but have not led to resistance in the field because they are applied selectively and only when there is a pest outbreak. Bt plants on the other hand, expose pests to the Bt toxin throughout the growing season and are much more likely to lead to resistance. It is perhaps for this reason that EPA has not regulated Bt foliar sprays, but has imposed restrictions on how Bt crops should be used.

Our analysis indicates that the level of "care" that Monsanto would exercise in the use of its Bt technology, relative to the socially optimal level of "care," depends on the availability of future Bt technologies. If there were not many backup technologies available after the current one is exhausted, then Monsanto would behave more conservatively than the social planner in ensuring that resistance management plans were implemented carefully and delay the setup of the next pool. However, if many backup technologies were going to become available, then we would expect that Monsanto would care less about resistance than the social planner and be more impatient to move on to future revenue sources.

3 Model

The problem to be examined will be similar to that defined in Hartwick et al. and in Dasgupta et al., with a few notational differences. Each of N identical deposits has a stock of S units of the exhaustible resource. A setup cost of K must be incurred to set up exploitation of the deposit but need not be paid if the deposit goes unused. These costs can be easily thought of as setup or shutdown costs; in either case, the cost must be incurred before exploitation of the next pool can begin.[6] Since both of those papers have shown that setup costs make optimal exploitation of the resource pools occur in sequence, we begin with that assumption.

Let us present the exploitation problem in a general framework that can be applied to either the social planner or the monopolist. In each case, the authority maximizes its present discounted value of exploiting the sequence of resource pools. Let $u(q)$ represent the flow of utility to the authority generated by resource extraction level q, where $u(\cdot)$ is a strictly concave function. For the planner, this will represent the total surplus net of extraction costs; for the monopolist, it will be total revenue less extraction costs. These key differences in the definition of $u(q)$ will be the source of behavior differences. The discount rate, r, is equal to the market interest rate and is

[6] The setup costs here are invariant, changing over time only in present value terms. However, they could also be generalized to incorporate research costs that are a function of time. For example, Dasgupta et al. (1992) assume that a new technology can be brought online sooner with higher invention costs. Such variations would not change the intuition for the results in this paper.

positive and constant.

We present the problem as a recursive one. Let V represent the value of optimal extraction from the closing of the current deposit (at time T) onward. Let $U(S,T)$ represent the maximized value of exploiting the current deposit by time T. Given those values, $F(V)$ represents the value of current extraction from time 0 onward when the decision variables associated with the current deposit, including T, are optimally chosen:

$$F(V) = \max_{T \geq 0} \left\{ -K + U(S,T) + V e^{-rT} \right\}. \tag{1}$$

where

$$U(S,T) = \max_{q(t) \geq 0} \int_0^T u(q(t)) e^{-rt} dt \tag{2}$$

subject to

$$\int_0^T q(t) dt \leq S. \tag{3}$$

For the current deposit in the sequence, the problem can be written as a Lagrangian $L = \int_0^T u(q(t))e^{-rt}dt - \lambda \left(\int_0^T q(t)dt - S \right)$[7]. The first order conditions are

$$u'(q(t))e^{-rt} - \lambda = 0 \qquad \forall t, q(t) > 0 \tag{4}$$

where λ is the shadow value of the stock constraint. Together, these form the standard Hotelling result that the present value of marginal utility remains constant, thus defining $q(t)$ as a function of $q(T)$ and $T - t$:[8]

[7]An alternate formulation is to set this up as an optimal control problem. The current value Hamiltonian, which is $H = u(q(t)) - \delta q(t)$, yields the first-order conditions $u'(q(t)) = \delta$ and $\dot{\delta} = r\delta$. These equations, along with the constraint (3), yield the conditions for maxima obtained in equations (4)-(6).

[8]Specifically, for any $q(t) > 0$ and $q(T) > 0$, and strictly concave utility, $dq(t)/dq(T) = e^{-r(T-t)}u''(q(T))/u''(q(t)) > 0$.

$$u'(q(t))e^{-rt} = u'(q(T))e^{-rT}, \tag{5}$$

In other words, the greater the extraction in the last period, the greater extraction will be in all periods, and consequently the faster the resource pool will be exploited.

Next is the endpoint condition, the choice of when to finish the current pool and move on to the next, derived from maximizing the bracketed term of (1) with respect to T, producing $\partial U(S,T)/\partial T - rVe^{-rT} = 0$. With $\partial U(S,T)/\partial T = u(q(T))e^{-rT} - \lambda q(T)$, using (4) and simplifying, we get

$$u(q(T)) - u'(q(T))q(T) = rV, \tag{6}$$

which defines $q(T)$ as a function of V.[9] This equation represents the tradeoff from stretching out the current resource pool for a bit longer. The left-hand side reveals that one gets another time period of utility from extraction, the cost of which is the scarcity value of that extraction, since a little less must be consumed in the preceding periods to leave enough for the additional period. The right-hand side shows the other aspect of the tradeoff: one delays the receipt of the subsequent value stream for a period, the value of which is the investment return that stream would have generated in one period.

It will also be useful to define the following variable: $\psi(q(t)) \equiv u(q(t)) - u'(q(t))q(t)$. We consider utility functions (surplus and profits) that are strictly concave, begin at the origin, and have $u'(0)0 = 0$. Under these conditions, $\psi(q(t)) \geq 0$ and rises as $q(t)$ rises, with $\psi(0) = 0$ and $\psi'(q(t)) > 0, \ \forall q(t) > 0$. Given the strict concavity of $u(\cdot)$, (4) implies that $q(t)$ declines monotonically as t rises throughout the interval $[0,T)$, and production is smallest at the time of shutdown (T). Therefore, $\psi(q(t))$ declines as t rises and reaches its smallest point at shutdown, when (rewriting (6)) we have

$$\psi\left(q\left(T\right)\right) = rV. \tag{7}$$

[9] As in Dasgupta et al. (1982), since the optimal paths display discontinuities, we adopt for notational convenience $f(t) = \limsup_{\tau\to t} f(\tau)$ for a function f.

Finally, to pin down T, a third equation is required, namely the constraint that the sum of the quantities extracted over time must equal the total stock of the resource available, or (3) holding with equality.

3.1 Planner's Problem

Social welfare equals the present value of the utility flows generated by the resource consumption net of setup costs. Utility can be considered the combination of consumer and producer surplus, or the area under the demand curve minus total variable costs, or

$$u_S(q) = \int_0^q P(s)ds - c(q). \tag{8}$$

(Note that the normal assumptions of downward-sloping demand and convex costs satisfy the assumption that utility is strictly concave). In this formulation, the marginal value of the last unit equals the market price minus the marginal cost: $u'_S(q) = P(q) - c'(q)$. Furthermore,

$$\psi_S(q) = \int_0^q P(s)ds - c(q) - (P(q) - c'(q))q. \tag{9}$$

The key first-order conditions for the planner then require that the present value of the marginal rents remain constant over time ($P(q(t)) - c'(q(t)) = (P(q(T)) - c'(q(T)))e^{-r(T-t)}$), and that the excess of the total surplus from extraction in the last period over the total scarcity value of that extraction equal the annualized value of the subsequent welfare stream ($\psi_S(q(T)) = rV_S$).

3.2 Monopolist's Problem

Rather than maximizing surplus, the monopolist maximizes profits, total revenues net of total costs:

$$u_M(q) = P(q)q - c(q). \tag{10}$$

Substituting into (5), we see that the present value of marginal revenue net of marginal costs (marginal profits) remains constant: $(P(q(t))+P'(q(t))q(t)-c'(q(t))) = (P(q(T))+P'(q(T))q(T)-c'(q(T)))e^{-r(T-t)}$. The steepness of this extraction path compared to the planner's depends on how the path of marginal revenue compares to price.

For the monopolist,

$$\psi_M(q) = -P'(q)q^2 - c(q) + c'(q)q. \tag{11}$$

From here we see that comparing the incentives for final extraction depends on both the differences in the functions $\psi_M(q)$ and $\psi_S(q)$ and in the values V_M and V_S.

Given any subsequent value stream, the monopolist would extract less at the end of the current pool if $\psi_M(q) > \psi_S(q)$ for all q. Substituting, we see that this holds if:

$$-P'(q)q^2 > \int_0^q P(s)ds - P(q)q \tag{12}$$

This equation can be reinterpreted as $(P-MR)q > CS$. That is, total revenue minus marginal revenue times the quantity sold (the area between marginal revenue and price), compared to consumer surplus (the area between the demand curve and the price). This condition will hold, for example, with linear demand, but not with all demand functions (including constant elasticity demand).[10]

Next, since total surplus is always greater than profits, the value of subsequent extraction is always greater for the planner than for the monopolist. To show this proposition, let n equal the number of resource stocks left in the sequence. Superscripts will denote periods or stocks until the end of the sequence; for example, for $q^n(t)$, the term t within parentheses will continue to represent time within the period and the superscript will signify the period in question. The value of maximized current and subsequent extraction, V^n, equals the greater of $F(V^{n-1})$ and V^{n-1}, since foregoing extraction of the current deposit and proceeding straight to the next is always an option.

Proposition 1 *For any remaining number of resource pools, $V_S^n > V_M^n$.*

[10]This equation reveals an important distinction compared to the backstop technology model of Dasgupta et al. (1982).

Proof. Let $V_S^n(q_x^N(t), \forall t \in [0, T_x^N); \forall N \in [n, 0])$ be the social value of the extraction path x. For any q, by (8) and (10), $u_S(q) > u_M(q)$. Thus, $V_S^n(q_M^N(t), \forall t \in [0, T_M^N); \forall N \in [n, 0]) > V_M^n(q_M^N(t), \forall t \in [0, T_M^N); \forall N \in [n, 0])$. By the definition of optimality, $V_S^n(q_S^N(t), \forall t \in [0, T_S^N); \forall N \in [n, 0]) > V_S^n(q_M^N(t), \forall t \in [0, T_M^N); \forall N \in [n, 0])$. Thus, it must be that $V_S^n > V_M^n$, for any n. ■

In other words, since total surplus always exceeds total revenue, along the monopolist's optimal extraction path, the discounted stream of social surplus exceeds that of profits. Furthermore, the stream of social surplus can only be higher along the planner's optimal path. Hence, the social planner always values subsequent extraction more than the monopolist.

For a given resource pool in the sequence, three factors determine whether the monopolist extracts slower or faster than the planner:

1. whether and how much the rate of decrease in the monopolist's extraction is slower than for the planner, during the exploitation of a particular resource pool;[11]
2. whether and how much $\psi_M(q) < \psi_S(q)$; and
3. how much $V_S > V_M$.

When all three factors hold (which requires certain demand conditions) the monopolist will always follow a more conservationist path of extraction and delay the introduction of new resource pools compared with a social planner. In reverse order, the monopolist has less incentive to hurry to the next pool, would extract less at the end of a pool anyway, and would want to follow a flatter extraction path than the planner. In this case, $T_M^n > T_S^n$ for all n, as shown in the following proposition.

Proposition 2 *Since $V_S^n > V_M^n$, two additional conditions are sufficient for $T_M^n > T_S^n$ for all n: 1) for any T and S, $-dq_M(t)/dt \leq -dq_S(t)/dt$ for $t \in [0, T)$, and 2) $\psi_M(q) \geq \psi_S(q)$ for $q > 0$.*

[11] Given any fixed time horizon, if the monopolist has a conservative bias at the beginning, then output at the end of the horizon must be greater than that of the planner (see Sweeney (1977) and also Dasgupta et al. (1982)). This bias can be switched toward less conservation using extraction costs and/or demand with increasing elasticity (see Lewis, Matthews and Burness (1979) and Fischer and Laxminarayan (2004)). However, if the resource is durable, competitive arbitrage can rule out that price would rise faster than the interest rate, so when variable extraction costs are absent, the monopolist can initially extract no faster than the planner (Stiglitz (1976)).

Proof. Let $z_i(V)$ solve $\psi_i(z_i) = V$. If $\psi_M(q) \geq \psi_S(q)$ for all $q > 0$, and since $\psi_i'(q) > 0$ for all i, then $z_M(V_M) < z_S(V_M)$. Since $V_S^n > V_M^n$, $z_S(V_M) < z_S(V_S)$. Thus, $q_M^n(T_M^n) = z_M(V_M^n) < z_S(V_S^n) = q_S^n(T_S^n)$. Suppose $T_M^n = T_S^n$. Then for the stock constraint to bind with $q_M^n(T_S^n) < q_S^n(T_S^n)$, it must be that $q_M^n(t) > q_S^n(t)$ for some t. However, this requires that the monopolist follow a steeper extraction path with $-dq_M(t)/dt > -dq_S(t)/dt$ for some t, which violates the first condition. Thus, to fulfill the stock constraint under these conditions, it must be that $T_M^n > T_S^n$. ■

However, when one of these additional conditions does not hold, it is possible that the monopolist may exhaust the resource more quickly. Furthermore, this possibility may depend on how many new options will follow the current pool. To demonstrate these results, it is useful to employ the constant-elasticity demand case with no variable costs, as in Stiglitz (1976). This scenario is a nice benchmark, since in the absense of setup costs, the planner and the monopolist would behave identically; then, we can see how setup costs cause these incentives to diverge.

4 Constant-Elasticity Demand, Zero Cost Case

As Stiglitz (1976), we will consider the specific case of no extraction costs and a price function with constant elasticity of demand, such as $P(q) = q^{-\frac{1}{\eta}}$,where $\eta > 1$ to guarantee that the monopolist's utility function (total revenue) is increasing and concave in output. With this demand function,

$$u_S(q) = \frac{\eta}{\eta - 1} q^{1-\frac{1}{\eta}}; \tag{13}$$

$$u_M(q) = q^{1-\frac{1}{\eta}}. \tag{14}$$

Let us now evaluate the three factors that determine the speed of extraction.

First, the rate of decrease in consumption is determined by the first-order conditions for output. Since variable costs are absent, the planner wants price to rise at the rate of interest, while the monopolist wants marginal revenue to rise at the rate of interest. As in Stiglitz, solving for $q(t)$, we see that in both cases

$$q(t) = q(T)e^{\eta r(T-t)}. \tag{15}$$

Thus, item 1 is not at issue, since given any $q(T)$, monopolist and planner would follow an identical path of extraction, which then also would ensure the same time horizon for exhaustion. Furthermore, if at any point in time extraction is greater for the monopolist than for the planner, then the monopolist's extraction must be greater for the entire time of the extraction horizon. Thus, the monopolist's horizon for a given pool is then shorter (longer) if $q_M(T)$ is larger (smaller) than $q_S(T)$.

Second, we note that

$$\psi_M(q) = \frac{1}{\eta}q^{1-\frac{1}{\eta}} < (\frac{1}{\eta - 1})q^{1-\frac{1}{\eta}} = \psi_S(q). \tag{16}$$

This result means that, for any given subsequent value, the monopolist would end with higher production, which then implies from (15) and the stock constraint that the extraction horizon for the current pool will be shorter.

Third, we have shown that the value stream is always smaller for the monopolist than the planner, who cares about total surplus. Thus, the second and third factors push the monopolist's extraction decision in different directions. Since the value of the subsequent resource sequence changes over time, which factor dominates can depend on how many resource pools are available. To see this result, we evaluate the incentives for each actor in the polar cases of a single remaining resource pool and an infinite number of pools.

4.1 One Remaining Resource Pool

Let us compare the incentives for the planner and the monopolist in the penultimate period. The values obtained after all extraction is completed are $V_M^{-1} = V_S^{-1} = 0$, since no gain or loss is expected after all sources of the resource are depleted. As a consequence, optimal actions in the last period ($n = 0$) merely maximize use of the last pool and are determined independently of

K:[12] $V^0 = F(0) > 0$. For this reason, and since marginal utility goes to infinity with constant-elasticity demand, the appropriate horizon of the last pool is infinity ($T^0 = \infty$). Furthermore, the value of the last deposit's extraction must be positive—and at least as great as the setup cost—or exploitation of the resource would not be worthwhile. Since K does determine the ultimate value of V^0, optimal actions in the penultimate period (and all preceding periods) will depend on K: $V^1 = F(V^0)$.

Recall the endpoint condition for the penultimate period:

$$\psi(q(T^1)) = rV^0 = r\left(\int_0^\infty u(q(t))e^{-rt}dt - K\right) \tag{17}$$

With constant elasticity of demand, the monopolist and planner will follow the same extraction path for the last resource pool. Since extraction will get infinitesimally small over the infinite horizon, it will be useful to express current extraction as a function of initial consumption:

$$q(t) = q(0)e^{-\eta rt}. \tag{18}$$

With the stock constraint, we can then also solve for q_0:

$$\int_0^\infty (q(t))dt = \frac{q(0)}{\eta r} = S,$$

or $q_0 = \eta rS$. So, to summarize, $q(t) = \eta rSe^{-\eta rt}$.

[12] This analysis holds for both setup and shutdown costs. The shutdown costs of the last deposit are postponed indefinitely and thus avoided; the problem thus returns to one of setup costs, where the previous deposit's shutdown costs are the next one's setup costs. Since only subsequent values affect extraction decisions, the optimal paths will be identical. Of course, which pool the costs are associated with is important for the determination of profits of the first and last. Furthermore, a competitive firm may want to avoid shutdown costs regardless of position. The point is, even abstracting from the complications of the finite horizon which make perfect competition implausible, the nonexistence result holds.

4.1.1 Planner

Using (13) to solve for the value to the planner of the last resource pool, we get

$$V_S^0 = \int_0^\infty \frac{\eta}{\eta - 1}((\eta r S)e^{-\eta r t})^{\frac{\eta-1}{\eta}} e^{-rt} dt - K = \frac{(\eta r S)^{\frac{\eta-1}{\eta}}}{(\eta - 1)r} - K \tag{19}$$

Substituting the expressions from (19) and (16) into the optimal stopping time (17), and solving for $q_S^1(T)$ yields

$$q_S^1(T_S^1) = \left((\eta r S)^{\frac{\eta-1}{\eta}} - r(\eta - 1)K\right)^{\frac{\eta}{\eta-1}} . \tag{20}$$

4.1.2 Monopolist

Using (14) to solve for the value to the monopolist of exploiting the last resource pool,

$$V_M^0 = \int_0^\infty ((\eta r S)e^{-\eta r t})^{\frac{\eta-1}{\eta}} e^{-rt} dt - K = \frac{(\eta r S)^{\frac{\eta-1}{\eta}}}{\eta r} - K \tag{21}$$

Substituting the expressions from (21) and (16) into the monopolist's optimal stopping time, and solving for $q_M^1(T_M^1)$ we get

$$q_M^1(T_M^1) = \left((\eta r S)^{\frac{\eta-1}{\eta}} - r\eta K\right)^{\frac{\eta}{\eta-1}} \tag{22}$$

Since $q_M^1(T_M^1) < q_S^1(T_S^1)$, the monopolist wants to switch pools at a lower extraction rate than the planner. By (15), then, the monopolist extracts less in each period, which then implies that the horizon must also be longer, $T_M^1 > T_S^1$.

4.2 Infinite Number of Resource Pools

Consider the case where there is an infinite number of the resource pools.[13] Municipal landfills are an example easy to visualize: they have limited capacity (the resource stock), another one can

[13]Note that even though the number of resource pools (and therefore the total amount of the resource) is infinite, the stock of each individual pool is finite. Furthermore, with setup costs, scarce factors in the economy must be employed to exploit each pool. Therefore, infinite amounts will not be extracted in any period.

always be built, but it does not make sense to have more than one serving the municipality at a time, since large costs must be incurred for construction and for containment at closure. Antibiotics or biotech products are another example: each one loses effectiveness over time as resistance builds up with use; however, with setup costs of research and development, a new product can be made available.

With an infinite number of future landfills, the incentives for each landfill are identical since the value stream of the subsequent infinite landfills is always the same. In a stationary solution, $F(V) = V$: the function maps V back into itself. From the first equation, one can solve for that V:

$$V = \frac{U(S,T) - K}{1 - e^{-rT}}. \tag{23}$$

Setting this stationary value of V equal to that derived from the individual endpoint condition (6), along with the first-order condition (15) and the constraint (3), gives three equations in three unknowns $q(T)$, $q(t)$, and T, given exogenous values of K and S.

4.2.1 Planner

Substituting from (13), we get the present value of the total surplus from a single resource pool, in equilibrium:

$$U_S(S,T) = \frac{e^{-rT}(q(T))^{1-\frac{1}{n}}(e^{\eta rT} - 1)}{(\eta - 1)r}. \tag{24}$$

Substituting the values from (24) and (16) into (6) and solving for the optimal final extraction yields

$$q_S^*(T_S^*) = \left(\frac{r(\eta - 1)K}{e^{(\eta-1)rT_S^*} - 1}\right)^{\frac{\eta}{\eta-1}}. \tag{25}$$

4.2.2 Monopolist

Substituting from (14), we get the present value of the revenue from a single resource pool, in equilibrium:

$$U_M(S,T) = \frac{e^{-rT}(q(T))^{1-\frac{1}{n}}(e^{\eta rT} - 1)}{\eta r}. \tag{26}$$

Next, substituting the expressions from (26) and (16) into (6) and rearranging yields the monopolist's optimal final level of extraction:

$$q_M^*(T_M^*) = \left(\frac{r\eta K}{e^{(\eta-1)rT_M^*} - 1} \right)^{\frac{\eta}{\eta-1}} \tag{27}$$

In this case, $q_M^1(T_M^1) > q_S^1(T_S^1)$, and the monopolist wants to switch pools at a higher extraction rate than the planner. By (15), then, the monopolist extracts more in each period, which then implies that the horizon must also be shorter $T_M^* < T_S^*$.

Thus, the future stream of revenues is relatively smaller compared to the fixed costs the fewer pools remain, and this effect is stronger compared to the future stream of utility net of fixed costs. Therefore, compared to the planner, the monopolist is more conservationist when only a few pools remain, and exploits them faster when they are plentiful.

5 Conclusion

The monopolist reacts differently to setup costs in exploiting exhaustible resources than would a social planner. Understanding how is important, since setup costs make competitive provision unlikely for a resource that does not exhibit significant, increasing variable costs of extraction. This situation can occur in some traditional resource markets, but it is perhaps more common for newer resources like antibiotics or biotech products. For these products, the major costs are incurred in the development process, rather than production. Once complete, patents ensure the developer a monopoly over provision of the product. Furthermore, scarcity is an important issue, since consumption depletes the resource—resistance increases with greater use of antibiotics or of crops genetically engineered to repel pests.

How the monopolist's incentives differ from those of the social planner depends on several factors. First is question of how the scarcity value affects the path of consumption. For the monopolist, marginal profits rise at the rate of interest during the exploitation of a particular resource pool. Depending on the structure of demand and extraction costs, this can lead to either a faster or slower extraction path than the planner. However, even with identical scarcity incentives, as in the case with constant-elasticity demand and no extraction costs, extraction can differ according to the incentives for timing the switchover to the next resource pool. These incentives involve tradeoffs between prolonging the life of the current resource pool and postponing moving on to the next one.

Prolonging use of the current pool means another period of profits, but that extraction comes at a cost of slightly less extraction—and thereby profits—in all the preceding periods over the life of the resource pool. This net effect can be larger or smaller than the net benefits to the planner of prolonging use of a pool, which involve the excess of total surplus in the last period over the scarcity value (marginal surplus) of the last period's extraction. Postponing the switch to the next resource pool postpones not only incurring the setup cost, but also receiving the present value of that resource pool and all the subsequent ones. Thus, for the monopolist, waiting one more period means giving up the interest that would have been gained on the value of the subsequent profit stream, which is necessarily less than the subsequent stream of surplus for the planner. This latter effect tends to make the monopolist more patient—and thus more conservationist than the planner—since the costs of postponing are smaller.

The overall effect then depends on the relative magnitudes of these differences. With certain forms of demand, like the constant-elasticity case, the monopolist's net benefits of prolonging use of the existing pool are smaller than those of the planner. When the costs of postponing the switch are relatively small, as when there are fewer resource pools left in the queue, the monopolist prefers to wait longer and conserve the existing pool. However, when the opportunity costs of postponing loom relatively larger, as when many more resource pools will be available, the monopolist becomes more impatient than the planner and follows a less conservationist path. The assumption of the constant-elasticity demand function is useful for analytical convenience that the monopolist's and social planner's incentives are perfectly aligned in case of zero setup costs. However, assuming a different demand specification would not alter our basic result that the availability of a large number of additional resource pools, each with its own setup costs, would imply a relatively faster rate of extraction for the monopolist (relative to the social planner), than if there were few additional resource pools.

For resources like biotech products, an important research question is whether the patent system offers good incentives for the monopolist to exercise the proper care for managing resistance and inventing new substitutes. This question has been raised not only regarding agricultural biotech products, but also in the case of antibiotics and the need for direct regulation for drug resistance.[14] The extensive use and misuse of antibiotics has resulted in rapidly increasing levels of bacterial resistance to these valuable drugs that form the bedrock of modern medicine. Pharmaceutical firms, which typically have seven to ten years to recover the significant investments made in drug development, may have insufficient incentives to care about drug resistance. Some have suggested the extending patent length or breadth on antibiotics may give pharmaceutical firms a greater incentive to conserve the effectiveness of their products (Tisdell 1982, OTA, 1995, Laxminarayan 2002). The results of this paper indicate that extending the firm's patent on antibiotics may or may not be in society's best interests depending on whether or not there are derivatives of the existing product that could be modified to counter the effects of drug resistance.

This paper indicates that more needs to be understood regarding not only the structure of demand but also the scope for future technologies. For example, a new antibiotic is often a variation of the same basic chemical entity; the scope for new derivatives not subject to the same resistance may then naturally be limited. Furthermore, in view of the uncertain nature of the arrival time and quality of new discoveries in the real world, future research is needed to understand how a monopolist may respond to these uncertainties compared to society's preference. These questions involve not only investment strategies, but also how early arrivals of substitute resources affect the use of current stocks—are they abandoned, exploited simultaneously, or exhausted while the new patent "sleeps"? More generally, our results indicate that the characteristics of a new invention—specifically, whether or not it is depletable—are important for determining whether the monopolist

[14] We recognize that patent protection is not necessarily the same as monopoly power although it could be the case in cases where there are few substitutes for the innovation. An important difference between the current situation with antibiotics and the Bt example described earlier is that while Monsanto has few (if any) competitors for the Bt transgenic technology, most innovators of new antibiotics may have to face competition from other manufacturers. However, with rapidly increasing resistance to many antibiotics, the situation could change to one where resistance induced obsolence results in patent protection also confering some degree of monopoly power.

is indeed a conservationist’s friend.

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