Sequential Development and Exploitation of an Exhaustible Resource: 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.

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1 Introduction

Many traditional natural resources involve significant setup costs—fixed costs of exploration and development that must be incurred before any extraction can begin. This situation is also prevalent for new kinds of resources like antibiotics or crops genetically engineered to repel pests. Major investments in research and development, as well as the approval process, must occur before the products can be brought to market. Furthermore, these resources are depletable, 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).

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. Therefore the average rate of increase is less than the interest rate. Since setup costs create a nonconvexity, they indicated and Fischer (2000) proved 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. In the case of drugs and biotech products, the patent system will ensure monopoly provision of the resource. This paper analyzes the exploitation path that would occur with monopoly ownership of the resource pools and compares it to the planner's problem.

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, Matthews, and Burness (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 setup costs in monopoly provision has received relatively little attention.

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 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 begin by analyzing the general problem of sequential exploitation for both the planner and the monopolist. 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 the presence of setup costs causes the monopolist to behave differently, 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 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 $\bar{S}$ 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.[1] 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 consumer 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 positive and constant.

Let V represent the value of optimal extraction from the closing of the current deposit (at time T) onward. Given that value, $F(V)$ represents the value of current extraction from time 0 onward when the decision variables associated with the current deposit, T and $q(t)$ for $t \in [0, T)$, are optimally chosen:

$$F(V) = \max_{q(t)\geq 0, T\geq 0} \left\{ -K + \int_0^T u(q(t))e^{-rt}dt + Ve^{-rT} - \lambda \left(\int_0^T q(t)dt - \bar{S} \right) \right\}. \tag{1}$$

For the current deposit in the sequence, first-order and endpoint conditions are obtained from differentiating the bracketed term with respect to $q(t)$:

$$u'(q(t))e^{-rt} - \lambda = 0 \qquad \forall t, \tag{2}$$

and T:

$$u(q(T))e^{-rT} - rVe^{-rT} - \lambda q(T) = 0. \tag{3}$$

[1] Although the setup costs here change over time only in present value terms, they could also be generalized to incorporate increasing research costs to bringing a new technology online sooner (as in the invention costs $x(T)$ in Dasgupta et al.). The intuition for the results in this paper remains the same.

From these conditions, two key equations are derived:

$$u'(q(t))e^{-rt} = u'(q(T))e^{-rT}, \tag{4}$$

which is the standard Hotelling result that the present value of marginal utility remains constant, thus defining $q(t)$ as a function of $q(T)$, and

$$u(q(T)) - u'(q(T))q(T) = rV, \tag{5}$$

which defines $q(T)$ as a function of V. 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.

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:

$$\int_0^T q(t)dt = \bar{S}. \tag{6}$$

It will also be useful to define the following variable:

$$\psi(q(t)) = u(q(t)) - u'(q(t))q(t). \tag{7}$$

For any concave utility function beginning at the origin, assuming marginal utility is finite at that point, $\psi(q(t)) \geq 0$ and rises as $q(t)$ rises, so $\psi(0) = u(0) - u'(0)0 = 0$ and $\psi'(q(t)) = -u''(q(t))q(t) > 0,\ \forall q(t) > 0$.Given the strict concavity of $u(\cdot)$, (4) implies that $q(t)$ declines monotonically as t rises throughout the interval $[0, T)$, and thus production is smallest at the time of shutdown (T); therefore, $\psi(q(t))$ declines as t rises and reaches its smallest point at shutdown.

2.1 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 $u_S(q) = \int_0^q P(s)ds - c(q)$. (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, $\psi_S(q) = \int_0^q P(s)ds - c(q) - (P(q) - c'(q))q$.

The key first-order conditions for the planner are then

$$P(q(t)) - c'(q(t)) = (P(q(T)) - c'(q(T)))e^{-r(T-t)}, \tag{8}$$

that the present value of the marginal rents remains constant over time, and

$$\int_0^{q(T)} P(s)ds - c(q(T)) - (P(q(T)) - c'(q(T)))q(T) = rV_S, \tag{9}$$

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.

2.2 Monopolist's Problem

Rather than maximizing surplus, the monopolist maximizes profits, total revenues net of total costs: $u_M(q) = P(q(t))q(t) - c(q(t))$.

Substituting into (4), we get

$$(P(q(t)) + P'(q(t))q(t) - c'(q(t))) = (P(q(T)) + P'(q(T))q(T) - c'(q(T)))e^{-r(T-t)}. \tag{10}$$

In other words, the present value of marginal revenue net of marginal costs (marginal profits) remains constant, and this defines $q(t)$ as a function of $q(T)$. Thus, the greater the extraction rate at the endpoint, the more the monopolist will be extracting in all preceding periods, and the faster the total exploitation. The difference in incentives compared to the planner depends on how the path of marginal revenue compares to price.

For the monopolist, the endpoint condition dictates that the excess of total profits over marginal profits multiplied by extraction in the last period equal the annualized value of the subsequent profit stream. Substituting into (5), we get

$$-P'(q(T))q(T)^2 + c(q(T)) - c'(q(T))q(T) = rV_M, \tag{11}$$

which defines $q(T)$ as a function of V_M. We see here that, given an equivalent subsequent value stream ($V_M = V_S$), the monopolist would extract less in the last period 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 $(P - MR)q > CS - Pq$. That is, total revenue minus marginal revenue times the quantity sold (the area between marginal revenue and price), compared to consumer surplus net of total revenue (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).[2]

Finally, 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 subscript 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, $V_S^n > V_M^n$.*

Proof. Let $V_S^n(q_x^n(0), .., q_x^0(\infty), T_x^n, .., T_x^0)$ be the social value of the extraction path x. For any q, $u_S(q) > u_M(q)$. Thus, $V_S^n(q_M^n(0), .., T_M^n, ..) > V_M^n(q_M^n(0), .., T_M^n, ..)$. By the definition of optimality, $V_S^n(q_S^n(0), .., T_S^n, ..) > V_S^n(q_M^n(0), .., T_M^n, ..)$. Thus, it must be that $V_S^n > V_M^n$, for any n. ■

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

To summarize, 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;[3]
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 to a social planner.

Proposition 2 *Two conditions are sufficient for $T_M^n > T_S^n$ for all n: 1) for any T and S, $-\overset{\circ}{q}_M \leq -\overset{\circ}{q}_S$, and 2) $\psi_M(q) \leq \psi_S(q)$.*

Proof. Let $z_i(V)$ solve $\psi_i(z_i) = V$. If $\psi_M(q) > \psi_S(q)$ for all q, 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 $q_M^n(0) > q_S^n(0)$. However, this violates the first condition. Thus, to fulfill the stock constraint, it must be that $T_M^n > T_S^n$. ■

However, when these conditions do not both 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.

[3] 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 (2002)). 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.

3 Constant-Elasticity Demand 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. From the planner's equations, we have that price rises at the rate of interest, or $q(t)^{-\frac{1}{\eta}} e^{-rt} = q(T)^{-\frac{1}{\eta}} e^{-rT}$, from which we solve for $q(t)$:

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

Meanwhile, the monopolist's requirement that marginal revenue rise at the rate of interest reduces to $\frac{\eta-1}{\eta} q(t)^{-\frac{1}{\eta}} e^{-rt} = \frac{\eta-1}{\eta} q(T)^{-\frac{1}{\eta}} e^{-rT}$, which results in the same condition as for the planner in (15). Thus, item 1 is not at issue, since the path of extraction would be identical over time, given the same $q(T)$, which then also ensures the same time horizon of extraction for exhaustion. Furthermore, since the price must rise at the rate of interest, if extraction is greater and the price lower in any one period for the monopolist than for the planner, then prices must be lower and extraction greater in all periods for the monopolist.

Second, we check to see how the endpoint conditions vary, given any subsequent value of the resource sequence. In this case,

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

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.

3.1 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:[4] $V^0 = F(0) > 0$. 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 infinitessimally small over the infinite

[4]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.

horizon, it will be useful to express current extraction as a function of initial consumption:

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

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 $q_0 = \eta r S$.

3.1.1 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

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

3.1.2 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

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

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

3.2 Infinite Number of Resource Pools

Consider the case where there is an infinite number of the resource pools.[5] Municipal landfills are an example easy to visualize: they have limited capacity (the resource stock), another one can 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:

$$V = \frac{\int_0^T u(q(t))e^{-rt}dt - K}{1 - e^{-rT}}. \tag{23}$$

Setting this stationary value of V equal to that derived from the individual endpoint condition (5), along with the first-order condition (4) and the constraint (6), one can solve for $q(T)$ and T in terms of K and S. Thus, Equations (4), (6) and (23) define T, V, $q(T)$, and $q(t)$ for $t \in [0, T)$.

3.2.1 Planner

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

$$\int_0^T u_S(q(t))e^{-rt}dt = \frac{e^{-rT}(q(T))^{1-\frac{1}{n}}(e^{\eta rT} - 1)}{(\eta - 1)r}. \tag{24}$$

Substituting the values from (24) and (16) into (5) for the optimal stopping time, and solving for $q^*_S(T^*_S)$ yields

$$q^*_S(T^*_S) = \left(\frac{r(\eta - 1)K}{e^{(\eta-1)rT^*_S} - 1}\right)^{\frac{\eta}{\eta-1}}. \tag{25}$$

[5] 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.

3.2.2 Monopolist

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

$$\int_0^T P(q(t))q(t)e^{-rt}dt = \frac{e^{-rT}(q(T))^{1-\frac{1}{n}}(e^{\eta rT}-1)}{\eta r}. \tag{26}$$

Next, substituting the expressions from (26) and (16) into (5) for the optimal stopping time for the monopolist, and rearranging a bit, we get

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

Given any T, $q_M^*(T) > q_S^*(T)$, the monopolist wants to switch pools at a higher extraction rate than the planner. By the first order conditions, then, the monopolist extracts more in each period, which then implies that the horizon must also be shorter $T_M^* < T_S^*$.

Thus, in the short horizon, the future stream of revenues are relatively smaller compared to the fixed costs than in the longer horizon, 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.

4 Conclusion

The monopolist reacts differently to setup costs in exploiting exhaustible resources than a social planner would. 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 depend on several factors. First is 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. Thus, the second and third factors involve the tradeoffs of 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. Alone, this 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.

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 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. More generally, these results indicate that the characteristics of a new invention—specifically, whether or not it is depletable—are important for determining whether the monopolist is indeed a conservationist's friend.

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