

Hotelling's "Economics of Exhaustible Resources": Fifty Years Later

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I. Introduction

THERE ARE ONLY a few fields in economics whose antecedents can be traced to a single, seminal article. One such field is natural resource economics, which is currently experiencing an explosive revival of interest; its origin is widely recognized as Harold Hotelling's 1931 paper, "The Economics of Exhaustible Resources." On the fiftieth anniversary of the publication of Hotelling's paper, a review in the light of the many contributions that have emerged since the early 1970s seems appropriate. Specifically, we show how a large number of the questions asked about natural resources today were first raised by Hotelling. Focusing on three areas, we then demonstrate how contemporary economists have extended Hotelling's model to provide more general—or, in some cases, more precise—answers to these questions.

Although Hotelling's paper appeared a half-century ago, the current wave of interest in natural resource economics is less than ten years old. However, the debt to Hotelling is widely acknowledged. For example, Robert Solow's 1973 Ely Lecture, "The Economics of Resources or the Resources of Economics" (1974), begins with a quotation from Hotelling's article and discusses a number of issues raised there.

One might wonder why the interest has been only so recently renewed; why the 1931 article was neglected for so long. The reasons have to do with both substance and style. Hotelling was writing at the end of an era—which had in fact ended some 10 years earlier—characterized by a strong popular concern for the adequacy of the world's natural resource base. Events of the 1930s of course brought other concerns, and serious attention to problems of resource depletion had to wait for the energy and environmental

"crises" of the 1970s.¹ The neglect of Hotelling's work is probably also attributable to its difficulty, which limited its accessibility to only a few economists at that time. Though the basic idea is first stated non-technically, much of the article is an exercise in the calculus of variations—a mathematical tool not commonly found in economics journals until the 1950s, at the earliest.

Hotelling had a two-fold purpose in writing the 1931 paper: (1) to assess the policy debates arising out of the conservation movement and (2) to develop a theory of natural resources because, in his words, "the static-equilibrium type of economic theory . . . is plainly inadequate for an industry in which the indefinite maintenance of a steady rate of production is a physical impossibility . . ." (p. 139). Accordingly, he established the now-famous "Hotelling rule," which states that the price of an exhaustible resource must grow at a rate equal to the rate of interest, both along an efficient extraction path and in a competitive resource industry equilibrium. In symbols, this is

$$p_t = p_0 e^{rt}$$

where p_t is price in period t , p_0 is price in the initial period, and r is the rate of interest. He thus showed that the competitive resource owner would deplete at a socially optimal rate. Therefore, the conservationists' pleas for public intervention cannot be based on any inherent tendency

for competition to exploit a resource too rapidly, assuming no divergence between the private and social discount rates.

The Hotelling rule is just the simplest case treated by Hotelling and others. More generally, the royalty, or the price net of the cost of extracting the marginal unit of the resource, will grow at rate r .² Where extraction costs are negligible, this of course reduces to the equation in the text. The intuition, as stated by Hotelling, is that the present value of a unit extracted must be the same in all periods if there is to be no gain from shifting extraction among periods. For the present value of price, or price net of extraction cost, to be the same in all periods, the undiscounted value must be growing at precisely the rate of interest. Further, if demand is stable, output declines monotonically and, in any case, ultimately declines to zero (but only asymptotically if the demand curve does not intersect the price axis at a finite price).

Hotelling established this much, and a good deal more. Among the questions he treated are the effects on resource price and output paths of: (1) monopoly, (2) extraction costs that increase with cumulative production, (3) demand influenced by cumulative production (of durables like gold and diamonds), (4) fixed investments (as for example in developing a mine), and (5) a severance tax and a tax on the value of a mine. He also touched on the external effects related to the uncertainty surrounding resource discoveries.

Not all of these questions are treated in the same detail or at the same formal level. For example, the last question, of considerable interest to contemporary

¹ This is not to deny at least occasional interest in these problems by economists and others in the interim. Heavy depletion of a number of resources during the Second World War led to formation of the President's Materials Policy Commission, which in 1952, issued a five-volume report on projected resource consumption and supplies over the next 25 years. In the same vein were the early studies by Resources for the Future, the most comprehensive being a set of projections by Hans H. Landsberg, Leonard L. Fischman, and Joseph L. Fisher (1963). Theoretical discussions in the spirit of Hotelling began to appear in the 1960s (O. C. Herfindahl, 1967; Richard L. Gordon, 1967; Ronald G. Cummings, 1969).

² A similar result was obtained less formally, in an earlier article by L. C. Gray (1914). There is an interesting difference, however. Gray assumes a resource price constant over time and a marginal cost of extraction rising over quantities, at any time. The growth in the difference between price and marginal cost is then explained by movement back down the rising marginal cost curve, from period to period.

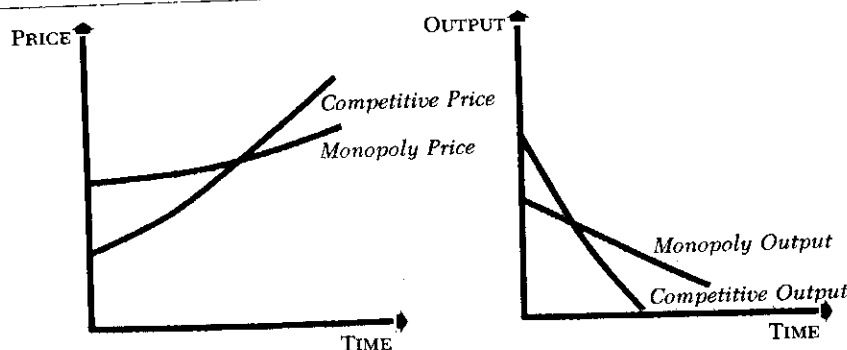


Figure 1. Competitive and Monopoly Price and Output Paths

theorists, is discussed only briefly and informally. By the same token, recent studies have devoted relatively little effort to questions of the effects on resource price and output paths of taxes or fixed investments.³

In the remainder of this paper we shall consider Hotelling's contributions and their relationship to more recent developments in three major areas. These are: the effects on price and output paths of: (1) monopoly, (2) demand and cost dependent on cumulative production, and (3) uncertainty, with special reference to externalities. We thus touch on most of Hotelling's questions with, however, a shift in emphasis reflecting the shift in interest within the profession.

II. Monopoly and the Rate of Depletion

The question as to how monopoly affects price and output paths is an important one, since monopoly episodes are not uncommon in the history of resource markets. A natural hypothesis is that a monopolist will restrict output and raise price, initially, as compared to a competitive industry. Price and output paths under monopoly and competition would

then look like the ones in Figure 1. The monopoly price path is flatter, and the rate of depletion is retarded.

This was in fact Hotelling's view. He recognized, as modern theorists have emphasized, that the outcome will depend on the nature of demand. For the monopolist, "Hotelling's Rule" is that marginal revenue, not price, will grow at the rate of interest. Then whether price rises more or less rapidly depends on the relationship between price and marginal revenue. Hotelling advances two reasons for believing that price will rise less rapidly, that depletion will be retarded, under monopoly.

First, he argues that demand may plausibly be such that the resource will be exhausted in finite time by a competitive industry, but only in infinite time by a monopolist. The condition for finite exhaustion under competition is that price is finite as quantity approaches zero, or in other words, that the demand curve intersects the vertical axis at a finite price. The condition for finite exhaustion under monopoly is that marginal revenue is finite as quantity approaches zero. Hotelling then suggests that it is quite likely that demand is such that the former condition is satisfied, but the latter is not. This is part of the "general tendency for production to be retarded under monopoly"

³ See, however, H. Stuart Burness (1976), and the volumes edited by M. Caffney (1967) on extractive resources and taxation and by Gerard M. Brannon (1975) on energy taxes.

(p. 152). No further analysis and no examples are provided. We have been unable to construct an example.

Hotelling's other reason for believing monopoly slows depletion comes from a numerical example of his own in which this occurs. In the example, both monopolist and competitive industry exhaust the resource in finite time, but the monopolist takes longer.

More recent treatments of the problem have focused on the general characteristics of demand required for a monopolist to deplete more slowly—or more rapidly, as the case may be. In particular, it has been shown that, if elasticity is decreasing as quantity increases, the monopolist will deplete more slowly (Tracy R. Lewis, 1976; P. S. Dasgupta and Geoffrey M. Heal, 1979). Hotelling's example, which features a linear demand curve, clearly falls in this category. Further, if demand is shifting over time, becoming more elastic, the same result follows (Milton C. Weinstein and Richard J. Zeckhauser, 1975; Joseph E. Stiglitz, 1976). The interpretation is that the monopolist takes advantage of the relatively inelastic demand in the early periods by restricting output then. By the same reasoning, decreasing elasticity (over time) would lead the monopolist to accelerate depletion in the early periods and to restrict output in the later periods. This result seems somewhat unrealistic for two reasons. First, substitutes for the resource are likely to become increasingly available. Second, accelerated depletion could mean that price would have to rise more rapidly than at the rate of interest. But this would create an opportunity for profitable arbitrage, so that it is not clear that such an equilibrium can be sustained (Dasgupta and Heal, 1979).

Our impression, then, is that recent contributions to the theory of monopolistic exploitation of an exhaustible resource tend to confirm Hotelling's original con-

clusion: monopoly slows depletion. They also provide greater insight into why this is likely to be so, however, and suggest conditions under which it may not be.

Hotelling also considered the intermediate case of just a few competing sellers, which he felt was "more closely related . . . to the real economic world" (p. 171) than either monopoly or perfect competition. An appropriate analytical treatment is merely sketched here, but invokes as a solution concept essentially a Cournot-Nash equilibrium, in which each mine owner is assumed to choose a production schedule to maximize his own profit, taking the schedules of the others as given. Interestingly, Hotelling suggests that the resulting equilibrium may in fact *not* be, since "each [seller], in modifying his conduct in accordance with what he thinks the others are going to do, may or may not take account of the effect upon their prices and policies of his own prospective acts" (p. 173). In particular, with an exhaustible supply and therefore less to lose by a temporary reduction in sales, a seller may well try to raise his price above the "theoretical" level in the expectation that his competitors will then raise their prices.

Though this is all very suggestive, no further formal analysis is provided. Oligopolistic depletion has been modeled in a number of recent contributions, but it seems fair to say that these owe relatively little to Hotelling. Most are motivated by OPEC, either explicitly or implicitly, in their treatment of a market made up of a dominant seller and a competitive fringe (Richard Schmalensee, 1976; Stephen W. Salant, 1976; Jacques Cremer and Martin L. Weitzman, 1976; Robert S. Pindyck, 1977; 1978a; Esteban Hnyilicza and Pindyck, 1976; Richard J. Gilbert, 1978; Gilbert and S. M. Goldman, 1978).

III. *The Effects of Cumulative Production*

Hotelling recognized that the mine owner's profit depends not only on the

current rate of production but also on the amount of cumulative production, or the stock remaining in the ground. He offered two reasons for this: (1) extraction costs increase "as the mine goes deeper" (p. 152), and (2) demand for resources like gold and diamonds, which are durables, is affected by the accumulated stock in circulation. Hotelling modeled these two effects in combination, by specifying that the "net price" (which is best thought of as average profit) depends on cumulative production. His successors, however, have analyzed the effects separately. Some look at the impact of past production on extraction costs; others examine the impact on demand price.

That extraction costs will rise as the stock of cumulative production grows was actually noted much earlier than 1931 and in a more general context by David Ricardo. Ricardo's model assumed the resource occurs in a variety of grades. As the historic production stock accumulates, higher grade ores get depleted and the producer resorts to lower grade ores, sustaining greater extraction costs.

The implicit assumption is that the best quality ores get depleted first. Hotelling must have had the same idea, since he assumed a negative sign governing the cumulative production term in his linear example of the net price equation. This result has been demonstrated more rigorously in a number of recent studies of the optimal depletion of deposits of different qualities (Herfindahl, 1967; Heal, 1976; Solow and Frederic Y. Wan, 1976; Weitzman, 1976; John M. Hartwick, 1978).

Modern theorists have also elaborated on the consequences for "Hotelling's Rule" of extraction costs rising with cumulative extraction for any reason. In these circumstances the royalty does not rise at the rate of interest, r , but at r less the percentage increase in cost caused by adding to the stock of cumulative production.

The earlier reasoning, that royalty rising at rate r equates the present value of extracting a unit of the resource in all time periods, no longer holds. The present value of extraction must take into account the higher extraction costs experienced in future time periods. The rate of increase in the royalty, therefore, must equal the opportunity cost of deferred extraction—foregone interest, r , less the savings in future extraction costs (Cummings, 1969; William D. Schulze, 1974; Weinstein and Zeckhauser, 1975; Frederick M. Peterson and Fisher, 1977; David Levhari and Nissan Liviatan, 1977).

So far, this section has considered contributions to Hotelling's cumulative production effect on the *supply* side. The effect on the demand side has received somewhat less attention, although two recent papers indicate that this may be a fruitful area of research in the future. If the demand for a resource is a function of the stock in circulation (i.e., the resource is a durable, like gold or silver) but that stock depreciates over time, Hotelling's r -percent rule still holds (Marion B. Stewart, 1980). Levhari and Pindyck, however, point out that the assumption of depreciation is crucial to this result (1979). Without depreciation, the resource stock will grow, forcing the price *down*—rather than allowing it to rise at the rate of interest. With a more general model, allowing for rising extraction costs, Levhari and Pindyck show that the price will fall. If the stock depreciates, price will follow a U-shaped trajectory. Interestingly, the same result tends to follow where the stock can be augmented by exploration. Price first falls as the major finds are made, but ultimately rises (Pindyck, 1978b).

Although Hotelling's successors have extended his analysis by separating the supply- and demand-side effects of cumulative production, some of Hotelling's questions remain unanswered. One of

these is the relationship between monopolistic and competitive extraction in the presence of this stock effect. Hotelling gave an example where the relationship is qualitatively the same—the monopolist extracts more slowly—as for the case with no stock effect. To the best of our knowledge, the question of whether this holds in general has not been explored.

IV. *Uncertainty and Exhaustible Resources*

Today much of the natural resources literature is concerned with the effects of uncertainty on the behavior of resource producers. While Hotelling raised this question in his 1931 paper, his analysis was heuristic and concentrated on just one aspect of this broad area. Contemporary economists, in addition to providing the theoretical backbone to Hotelling's conjectures, have posed—and answered—a richer variety of questions, thanks to major developments in the general area of decision-making under uncertainty. In this section, after highlighting Hotelling's contributions, we briefly survey the more recent papers, pointing to the larger set of concerns that they address.

In his introductory list of "intriguing problems" associated with exhaustible resources, Hotelling asked (p. 139):

What is the value of a mine when its contents are supposedly fully known, and *what is the effect of uncertainty of estimate?* [Italics added.]

The italicized question was not answered in Hotelling's paper. Instead, he focused on a particular form of "uncertainty of estimate"—exploration uncertainty—and examined its implications for public policy. Presumably, if the contents of a mine are unknown, the output of exploratory activity is uncertain.

The case treated by Hotelling where exploration uncertainty leads to market failure (and hence a justification for public

intervention) is an example of what is now called the common property problem:

Great wastes arise from the suddenness and unexpectedness of mineral discoveries, leading to wild rushes, immensely wasteful socially, to get hold of valuable property. [P. 144.]

The problem arises from the fact that whoever finds a mineral deposit can, by filing a claim, exclude competitors from access. Presumably this leads to socially excessive levels of exploratory activity.

Hotelling recognized another situation, stemming from exploration uncertainty, which may cause private levels of effort to deviate from the socially optimal ones. Owners of neighboring tracts benefit from the knowledge that exploration is, or is not, successful in a particular tract. Hotelling claimed that this spillover of geological information leads to excess profits, which should be appropriated by the government. In Hotelling's view, the profits of a "landowner who discovers the value of his subsoil purely by observing the results of his neighbors' mining and drilling" should not be allowed to "remain in private hands" (p. 144). Instead of concentrating on the distributional implications, Hotelling's successors have shown that the spillover effects of information can lead to socially deficient levels of exploratory effort: everyone waits around hoping his neighbor will drill first (Peterson, 1975; Stiglitz, 1975).

Although exploration uncertainty was the only type treated by Hotelling, it is but one of many kinds of uncertainty surrounding natural resources. Recently a sizeable literature has emerged dealing with other sources of uncertainty, which may be divided into two categories, uncertainty in supply and uncertainty in demand. Contributors to the former category essentially attempt to answer Hotelling's original question: what is the effect of "uncertainty in estimate" of the contents of a mine. If the resource is of

uniform quality, in fixed, albeit unknown size, the owner will deplete at a slower rate than if he knows—with certainty—that the size of the stock is the expected value of the prior probability distribution (Murray C. Kemp, 1976; Gilbert, 1979; Glenn C. Loury, 1978). The intuition here is that the uncertain owner follows a conservative depletion policy because he wants to avoid running out of the resource unexpectedly—somewhat like the behavior of a motorist driving without a gas gauge.

Of course, the natural extension of this approach is to allow for exploration. Although the size of the stock is unknown, the uncertainty may be reduced by exploration. Michael Hoel looks at the case where agents learn about the size of a second stock by depleting a known stock (1978). When exploration is costly, Kenneth Arrow and S. Chang show that, if discovery follows a Poisson process, the price of an exhaustible resource may follow a cyclic pattern (1978). Interestingly enough, the Arrow-Chang paper was motivated by the observation that, historically, resource prices have not followed the Hotelling r -percent rule. Other approaches to exploration uncertainty include those of Pindyck (1979), where exploratory output follows a continuous stochastic process, and Devarajan and Fisher (1980), where current exploratory inputs are related to future discovery outputs by a random production function.

Turning now to uncertainty in the demand for an exhaustible resource, the approaches and conclusions vary considerably. If future prices are uncertain but the near future is less uncertain than the distant future, the risk-averse owner accelerates depletion (Weinstein and Zeckhauser, 1975). On the other hand, if the random component in the demand function is identically distributed in each time-period, the risk-averse owner will shift extraction towards the future, when produc-

tion is otherwise lower and so, therefore, is the amount at risk (Lewis, 1977). Finally, Dasgupta and Heal (1974) and Ngo Van Long (1975) treat the case when demand for the resource may vanish suddenly—either from the introduction of an inexhaustible substitute or by expropriation. Not surprisingly, they conclude that such a threat leads to a bias towards current depletion.⁴

V. Concluding Remarks

As we have tried to show, Hotelling's elegant and comprehensive analysis, his wide-ranging conjectures and asides, make the 1931 analysis very nearly the sole source of work in a vigorously growing branch of economics. Although a determined search may turn up hints in other early works, it is hard to imagine another paper that not only presented the canonical model for modern theorists to build on, but also anticipated the relevant issues—such as the effects of uncertainty and the presence of externalities—by almost a generation.

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⁴ There are at least two other sorts of uncertainty, currently of great interest to resource economists, which affect depletion strategies. First, the possibility of government regulation when the price of the resource gets too high may accelerate current extraction. But this can be viewed as another interpretation of the possibility that an inexhaustible substitute will appear, preventing the price from exceeding a certain level. Second, the costs of transporting the resource from where it is extracted to its primary user may, under certain circumstances, become prohibitively high. For example, a war would make certain routes impassable. (This threat was responsible for the United States' stockpiling of minerals in strategic locations during World War II.) This form of uncertainty, though, can be interpreted as another way of looking at the threat of expropriation.

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