On the Empirical Significance of the Hotelling Rule

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Introduction

The origins of the field of nonrenewable resource economics can be traced to Harold Hotelling's (1931) "The Economics of Exhaustible Resources". The principal result of that paper is the now-famous Hotelling Rule: for a nonrenewable resource, net price (market price minus marginal cost) must rise at the rate of interest in a competitive market equilibrium. This basic rule forms the theoretical core of the economics of nonrenewable resources, is present in one form or another in every modern paper on nonrenewable resource economics, and is the conceptual and theoretical framework used by economists to understand and model the long-run evolution of prices and supplies for nonrenewable resources.

But what do we know about the empirical relevance of the Hotelling Rule? What practical insights has it provided for understanding what we have observed so far in nonrenewable resource markets? Does it help us understand the supply behavior of extractive firms and industries? The purpose of this article is to address these questions by reviewing the empirical evidence thus far and evaluating the empirical significance of the Hotelling Rule.

In the next section, I provide some intuition and additional background on the Hotelling Rule. This is followed by a discussion of the empirical evidence on market prices for nonrenewable resources. Next, I investigate the significance of technological change and market structure in influencing observed trends in prices. This is followed by an examination of the literature on empirical tests of the Hotelling Rule and a discussion of the Hotelling Valuation Principle (HVP). The final section draws conclusions about the empirical significance of the Hotelling Rule.

The Hotelling Rule: Intuition, Background, and Definitions

The intuition behind the Hotelling Rule is straightforward. Net price has to rise at the rate of interest as a condition of equilibrium; otherwise, the present value of the net price that could be received from selling in some periods would be higher than in other periods. In this case, mine owners would not be indifferent about when to extract and sell their resources. Another way to understand the Hotelling Rule is as a condition of intertemporal arbitrage

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that ensures that the last unit extracted in any time period earns the same return (in present value terms).

Hotelling's seminal article was a response to the conservation movement's claims that unregulated private markets would lead to the overexploitation of nonrenewable resource stocks, so it was natural for him to focus on the intertemporal allocation issue. Hotelling argued that the socially optimal rate of exploitation of a nonrenewable resource over time is achieved in a competitive market equilibrium, provided that the social discount rate equals the interest rate and that there are no sources of market failure such as externalities or incomplete property rights. Nearly 80 years later, the economics literature continues to focus on the intertemporal allocation aspects of nonrenewable resource supply and rely heavily on Hotelling's original insights.

The literature uses a number of names to refer to the concept of "net price": scarcity rent, shadow price, royalty, marginal user cost, and in the language of optimal control theory, the costate variable. In this article, I will use the term "scarcity rent." I will also use the term "interest rate" because that is what Hotelling used. However, the term "discount rate" is a commonly used substitute.

Hotelling recognized that he had constructed a highly stylized and, in some ways, overly simplified model of mining. For example, he pointed out that his basic model fails to capture the tendency for extraction costs to rise as a resource is extracted. This can occur both within an individual deposit, as the firm digs deeper or as pressure declines in a petroleum reservoir, and for the industry as a whole, as firms tend to use up the lowest-cost deposits first. This tendency for extraction costs to rise is often referred to as the degradation effect or the stock effect of extraction. When the Hotelling Rule is modified to incorporate this effect, scarcity rent rises less rapidly because current extraction now has an additional negative effect: it degrades the quality of remaining reserves—or raises the cost of future extraction. This implies that scarcity rent will rise less rapidly than the rate of interest in a competitive equilibrium. In fact, if the degradation effect is strong enough, scarcity rent may eventually decline.

This modification to the Hotelling model has significant implications for the way we think about depletion. It is not the finiteness of the exhaustible resource but rather the rising cost of extracting what is left that becomes the constraining factor. Economists recognize that we will probably never physically exhaust any exhaustible resource. Instead, economic exhaustion will occur when the cost of further extraction becomes higher than the market is willing to pay. Indeed, at this point, the scarcity rent itself becomes zero.

The Hotelling Rule, with and without these modifications, remains the underlying theoretical framework for our understanding of how markets for nonrenewable resources will evolve. Its most important empirical implication is that market price must rise over time in real terms, provided that costs are time-invariant. In the benchmark case of zero marginal cost and perfect competition, market price itself will rise at the rate of interest. With positive but time-invariant marginal cost, market price must rise at a rate proportional to but less than the rate of interest. When degradation effects are present, market price still rises over time even though scarcity rent may eventually decline to zero (Livernois and Martin 2001). Under imperfect competition, scarcity rent must still rise at the rate of interest, or slower if degradation effects are present; however, market price will typically start higher and rise less rapidly than under perfect competition.

Several other modifications and extensions to the basic Hotelling model have appeared in the literature that include factors such as imperfect competition, the presence of a backstop technology, different types of risk, durability of the mineral, recycling, and exploration. I will briefly discuss these extensions below as needed to facilitate the evaluation of the empirical literature.[1]

Empirical Evidence on Market Prices

Although the Hotelling model and the Hotelling Rule have been extended in many directions, the essential idea remains the same: in a market equilibrium, current price reflects both the marginal cost of extraction and the scarcity rent. In the basic model, there is a clear prediction that prices will rise over time to reflect both rising scarcity and a rising marginal extraction cost. What does the empirical literature tell us about prices?

Early Analyses of Mineral Resource Prices

The first systematic analysis of long-run trends for nonrenewable resource prices was conducted by Barnett and Morse (1963), who used price data from 1870 to 1957 for several commodities. Their interest was not in testing the Hotelling model per se, but rather in examining the hypothesis of increasing scarcity for natural resources. The concern was that rising resource scarcity, as reflected in rising costs and prices, would place a drag on economic prosperity and indeed growth. What they found was surprising. Despite the fact that mineral resources had been subject to exploitation for decades at increasingly rapid rates, mineral prices, in real terms, showed no discernible rising trend over the time period.

With the advantage of more sophisticated statistical techniques and a data set that spanned the period 1900 to 1973, Smith (1979) reevaluated Barnett and Morse's (1963) conclusions. He found no statistically stable time trend, either upwards or downwards, in the price index for minerals as a whole over this period and concluded that it was impossible to make inferences about changes in scarcity without detailed analysis of individual mineral commodities.

Evidence of *U*-Shaped Price Paths

Slade (1982) did this more detailed analysis, looking for trends in the prices of eleven major metals and fuels (aluminum, copper, iron, lead, nickel, silver, tin, zinc, coal, natural gas, and petroleum) from 1870 to 1978. She found that many of the price series seemed to bottom out in the 1960s but began to turn upwards in the 1970s. To reconcile these findings with the Hotelling Rule, Slade (1982) developed a modified version of the model in which both cost-increasing degradation effects and cost-reducing technological change are present. Since marginal cost can fall over time if the effect of technological change is greater than the degradation effect, Slade concluded that the price of the nonrenewable resource can fall initially, even if the Hotelling Rule is satisfied. However, Slade found that eventually the cost-reducing effect of technological change is overcome by the cost-increasing effects of depletion and/or the price-increasing effects of the Hotelling Rule, which means price will

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[1] For a more thorough discussion, see Krautkraemer (1998); and Gaudet (2007).

turn upwards. Overall, her model predicts that *U*-shaped price paths are consistent with the Hotelling Rule.

Another theoretical explanation for *U*-shaped price paths has been suggested by Pindyck (1978a); Livernois and Uhler (1987); and Swierzbinski and Mendelshohn (1989a). When exploration is added to the Hotelling model, even in a deterministic manner so that future discoveries are fully anticipated, the process of building up and then running down proven reserves can lead to a *U*-shaped price path. Deshmukh and Pliska (1980); Arrow and Chang (1982); Lasserre (1984); Swierzbinski and Mendelsohn (1989b); and Cairns and Quyen (1998) have shown that when discoveries are not fully anticipated, price jumps or falls occur as revisions to the expected stock of remaining reserves are made. If, as one might predict, the largest finds and the largest number of finds occur early,[2] then this might add further weight to the prediction of *U*-shaped price paths.

Evidence of Unit Roots

Slade's theoretical analysis and empirical findings of *U*-shaped price paths seemed to provide reassuring evidence that Hotelling's predictions were being borne out by the data. However, subsequent research has cast doubt on the statistical robustness of these empirical findings. Indeed, the empirical literature on price trends from this point forward concentrated on sorting out whether the statistical properties of these time-series data are stationary over time. Stationarity in a time series is important: it means we can confidently predict that its statistical properties will be the same in the future as in the past. If a *U*-shaped trend fits well using historical data (as in Slade's analysis), we can be confident that it is not just an artifact of the time period analyzed, but in fact provides a robust inference about the trend that prices are following.

The most commonly used statistical test to determine if a time series is stationary is the unit-root test.[3] Berck and Roberts (1996) performed this test for most of the commodity prices studied by Slade (1982), but with the advantage of thirteen additional years of data (1870–1991). They found evidence of unit roots in most of the price series and concluded that the *U*-shaped trend is not stationary. This implies that there is no statistical basis for concluding that prices have bottomed out and are starting to turn upwards.[4] Berck and Roberts (1996) found evidence that the year-to-year changes in prices were themselves stationary time series.[5] However, they were unable to find conclusive evidence from their analysis of these time-series data that price changes were tending to become positive during the sample period.

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[2] Even if exploration were completely random, the probability of finding large or any deposits would likely be larger simply because there are more of them early on.

[3] A unit root is present if the coefficient on the lagged value of the dependent variable (such as price) in a regression equation is equal to 1. This means that the effect of past shocks never wears off, so the dependent variable does not revert to a stationary value or, if a trend is controlled for, as in the case at hand, never reverts to a stable trend.

[4] A time series is said to have a stationary trend, or to be "trend-stationary," if it has a tendency to return to the trend, even after being subjected to random shocks. In subsequent papers, Slade (1988) and Agbeyegbe (1989) found similar evidence.

[5] This is also referred to as a "difference-stationary" time series.

Ahrens and Sharma (1997) take the story to the next level with their analysis of annual price data from 1870 to 1990 for the same set of eleven nonrenewable resources studied by Slade (1982). They argue that Berck and Roberts (1996) might have been wrong to conclude that unit roots were present in these price series. They cite Perron's (1989) finding that if a structural break is present in the price series but is not controlled for, tests are biased against rejecting the hypothesis of a unit root. After allowing for structural breaks at critical points such as the Great Depression (1929) and the outbreak (1939) and end (1945) of World War II, they reject the hypothesis of a unit root for six of the eleven commodity price series, which casts a doubt on Berck and Roberts' (1996) results. Going one step further with the same data and the same time period (1870–1990), Lee, List, and Strazicich (2006) allow structural breaks to be determined endogenously for each of the eleven price series and are able to reject the hypothesis of a unit root in all eleven cases. Their results imply that the price series are indeed trend-stationary after all, but only between the endogenously determined structural breaks. They find more downward than upward trends in the eleven price series. But these trends are punctuated by both upward and downward jumps at the structural break points, making it impossible to draw any general conclusions about whether prices are rising or falling.[6]

Problems with Using Price Indices

There are two potential problems associated with deflating nominal resource prices by a price index, an approach used in all of the studies discussed above. The first is that recent research has shown that standard price deflators overestimate the true extent of inflation for three reasons: first, price indices underestimate the extent to which consumers and producers are able to substitute away from goods or inputs that increase in price; second, price indices do not incorporate the introduction of new (and presumably more effective) goods and inputs except with a lag; and third, price indices do not adjust for improvements in the quality of goods or inputs. Using recent estimates in the literature of the size of the inflation bias to adjust the standard deflators downwards, Svedberg and Tilton (2006) find that the adjusted real price of copper follows a statistically significant rising trend from 1870 to 2000, whereas it falls over time using the unadjusted deflators. The second problem is that the standard deflation procedure implicitly assumes that nonrenewable resource prices adjust fully to changes in the general price level. Moazzami and Anderson (1994) argue that this is implausible in the short run and should be a tested hypothesis in the long run. Otherwise researchers could potentially create a specification error that could indeed be responsible for the nonstationarity found in the inflation-adjusted price-series data discussed above. Using the same data as Slade (1982) but with additional years of data, Moazzami and Anderson allow for short-run deviations from the long-run hypothesized trend and test whether the long-run relationship holds. They find that (a) most nominal resource prices do fully adjust to changes in the price index but only in the long run and (b) the data support the hypothesis of a *U*-shaped trend for most of the price series. Both the Moazzami and Anderson (1994); and the Svedberg and Tilton (2006) studies raise important questions about the measurement

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[6] See Figure 1 in Lee, List, and Strazicich (2006) for plots of the eleven price-series data with the structural breaks and fitted trends.

of relative prices for nonrenewable resources that deserve further attention before any firm conclusions can be drawn about upward or downward price trends.

Conclusions about Nonrenewable Resource Prices

Notwithstanding the measurement issues raised above, the findings in Lee, List, and Strazicich (2006) reflect the current state of knowledge concerning the empirical performance of nonrenewable resource prices. What do their findings tell us? First, there is no common pattern across the eleven commodity price series. Second, no price series unambiguously rises over time; only zinc comes close because it appears to have rising trends interrupted by two downward corrections. Third, one could argue that the price series for natural gas, petroleum, and possibly nickel have the look of a *V*-shaped (rather than a *U*-shaped path) and fourth, most prices are falling toward the end of the sample period (1990).

This last conclusion begs the question about what would happen if the analysis were extended to account for what has happened in commodity markets since 1990. This is clearly a question that needs to be addressed, and factoring recent data into a time-series analysis is a potentially fruitful area for future research. While such an analysis is beyond the scope of this article, I offer some observations here. Looking at the price data for the eleven commodities since 1990, one would have to conclude that the downward trends Lee, List, and Strazicich (2006) found in the period immediately preceding 1990 continued for the next decade or so. However, after 2001, all of the prices (with the exception of coal) have shown dramatic increases. For example, the annual average growth rates of prices in real terms (relative to the producer price index) from 2001 to 2007 have been 38 percent for aluminum, 36 percent for nickel, 32 percent for lead, 26 percent for copper, 22 percent for zinc, 19 percent for iron ore, 18 percent for tin and silver, and 16 percent for crude oil (UNCTAD and U.S. Energy Information Administration). These are very rapid growth rates indeed over a six-year period and the markets show no sign of abating as this article goes to press.

Does this mean nonrenewable resource prices have finally turned upward for good? Not likely. Although the Hotelling Rule tells us that nonrenewable resource prices will indeed eventually turn upwards, it cannot justify growth rates in prices as high as those observed recently. This, combined with the observation that commodity prices are highly volatile, suggests that it would be unwise to expect that prices will continue to rise unabated.

The Role of Technological Change in Price Trends

How significant is the role of technological change in explaining the declining relative price paths that have been observed for nonrenewable resources? To cause nonrenewable resource prices to fall relative to a price index, technological change would have to affect nonrenewable resource prices more than it affects the overall index of prices in the economy, and it would have to do this in the presence of cost-increasing degradation effects. Thus, it is a tall order for technological change alone to explain falling real nonrenewable resource prices.

Cost Effects of Technological Change

It is difficult to isolate the effect of technological improvements on costs in nonrenewable resource industries because we are only able to observe the net effect of technological improvement and resource degradation. However, a small number of studies have attempted to isolate the effects of technological change. Lasserre and Ouellette (1988) measured changes in total factor productivity (TFP) for the asbestos industry in Canada while controlling for changes in the quality of the resource as measured by ore grade. They found that the pure effect of technological improvement would have been a 76-percent increase in TFP from 1953 to 1982, an increase similar to what occurred in the textile sector, which was used as a comparable, nonresource sector. However, the net effect was only a 13-percent increase in TFP because of the effect of resource degradation. Schmitz (2005), on the other hand, found evidence of substantial improvements in productivity, including a doubling of labor productivity, in the iron ore industries in the Great Lakes Region. This occurred over a very short period of time in the early 1980s and resulted primarily from reorganization of work practices to meet rising competition from Brazilian exporters. In a very innovative study, Cuddington and Moss (2001) used data on the number of technological diffusions observed per year to isolate the effect of technological change on nonrenewable resource costs. They estimated that finding costs for natural gas would have risen by about 22 percent per year had it not been for technological change. Instead, gas-finding costs rose only by about 2.7 percent per year. It appears that the effect of technological change on finding costs for natural gas, while large, was not enough to outweigh the effects of degradation. Managi et al. (2004) advanced the Cuddington et al. methodology by using the relative importance of specific innovations as expressed by industry experts, rather than the raw number of innovations, as the control for technological change. Using a detailed micro-level data set for offshore oil and gas production in the Gulf of Mexico from 1947 to 1998, they found that technological change more than compensated for the effect of degradation. However, productivity growth in the industry averaged 0.2 percent per year, which was lower than the U.S. national average of 0.7 percent.

The evidence above suggests that technological change alone is not a sufficient explanation for falling real resource prices. If technological change were the only explanation, then nonrenewable resource prices should not have fallen relative to nonresource good prices (as measured by the producer price index). Even though the net effect of degradation and technological change often appears to be cost reducing, it is seldom as large as the effect of technological change on nonresource costs. Thus there is clearly more to the explanation for falling prices than technological change.

Other Factors That Affect Price Trends

Three other significant factors contribute to the explanation of falling prices. First, technological innovations occur at all stages of getting a natural resource product to market, from geophysical exploration to on-site drilling and mapping, development, extraction, and processing. The studies examined above all looked at the impact of technological change on a single stage. As shown in Lin and Wagner (2007), the net effects of technological change combined over all stages in nonrenewable resource production are potentially much larger than the above evidence would suggest. Lin and Wagner (2007) construct a model based on Slade's (1982) analysis that allows them to formally test the hypothesis that the opposing effects of technological improvement and resource degradation exactly offset one another. Using data on extraction costs and prices for a number of mineral commodities from 1970 to 2004, they are unable to reject the hypothesis, which is consistent with their finding of no discernible trend in real prices over this period.

A second factor is that technological innovation can change not only contemporaneous extraction costs, but expected future costs as well. This would lead to an upward reevaluation of the economically recoverable reserves and, hence, a downward adjustment to the value of scarcity rent. The point is that technological change can affect nonrenewable resource prices through at least two channels, first via its effect on current cost and second via its effect on scarcity rent (because of its effect on expected recoverable reserves). In the nonresource sector, technological change can operate only through the first channel. A third, and also unique, channel through which technological change may operate is by reducing the supply price of backstop technologies, which would lead to a further reduction in the current price of the nonrenewable resource.

The third factor is nonrenewable resource discoveries that are not anticipated. It is obvious that major unanticipated discoveries would have a significant downward effect on scarcity rent and hence market price. It is therefore surprising that one cannot find evidence of this in the economics literature or even attempts to determine the extent to which major discoveries could help explain observed prices over time for nonrenewable resources. This impact could be significant and warrants research. For example, Adelman (1993) reports that in 1987, the U.S. Geological Survey estimated that there was no more than a 5-percent probability that world's oil reserves remaining to be discovered and developed were as much as 222 billion barrels. Yet, I calculate that the world's oil production alone since 1988 has been 478 billion barrels and recent estimates of existing world proved reserves are in excess of 1,000 billion barrels (U.S. Energy Information Administration).

A Simulated Price Path for a Nonrenewable Resource

I conclude this section with a report on a simple experiment. I simulated the price path predicted by the basic Hotelling model after augmenting it to include some of the factors discussed above. In particular, I assumed fully anticipated technological change that reduces marginal cost over time at a decreasing rate. I assumed four unanticipated increases in recoverable reserves, which I modeled by extending the expected time to depletion, which in turn reduced the current value of scarcity rent. Finally, I added a small random error term with a zero mean to capture temporary supply and demand shocks.

Figure 1 shows the result of this Hotelling price equation simulated over 100 periods. If an econometrician were presented with the first fifty or sixty data points in this series, he or she would be hard pressed to find anything resembling what we would expect to see from a world in which the Hotelling Rule is operating. However, when we see the whole picture, we detect something resembling a *U*-shaped price path of the kind hypothesized by Slade (1982). Price eventually turns upward (though not smoothly) because unanticipated discoveries peter out, and because the effect of rising scarcity rent eventually dominates the effect of technological change. Overlaying this long-run trend are frequent short-run fluctuations caused by the random error term and less frequent but larger shocks caused by revisions to the expected stock of reserves remaining, which in turn leads to market corrections in scarcity rent and hence market price. The point is, without much effort and without resorting to a complicated

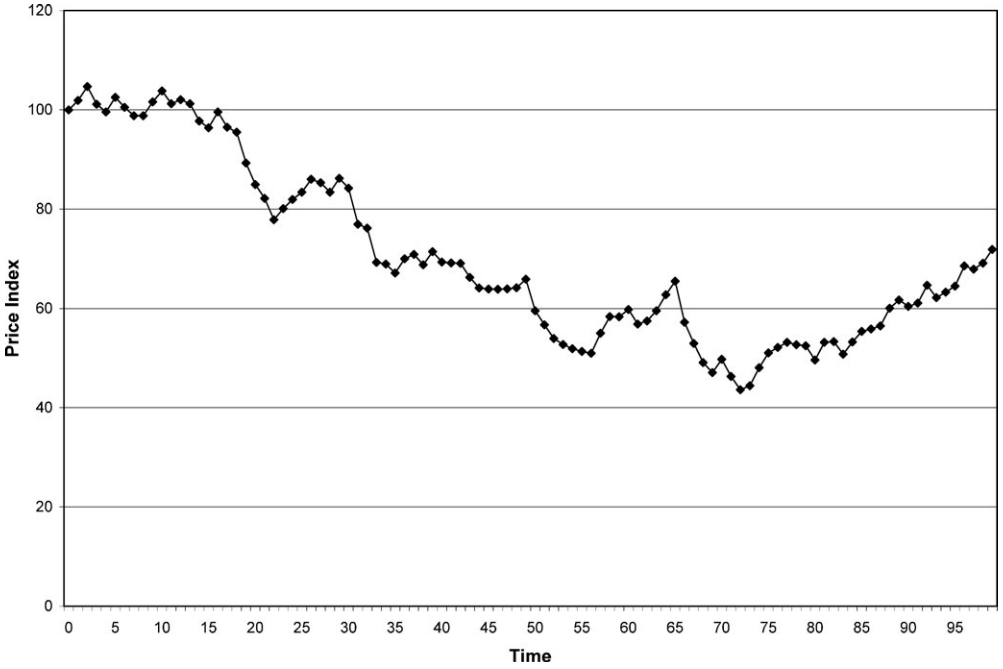

Figure 1. Simulated price path for a nonrenewable resource.
Source: Author's calculations.

modification of the Hotelling model, it is possible to generate price paths that do not look unlike the ones we have observed empirically.

The Role of Market Structure in Price Trends

The discussion so far has focused on the Hotelling Rule in the context of perfect competition, an assumption that may not be realistic for a number of nonrenewable resource industries. How is the empirical significance of the Hotelling Rule affected by the presence of imperfect competition? In particular, would it change what we expect to observe and could it contribute to the explanation of flat or falling real prices?

I will limit the discussion here to what I view as being the most salient points.[7] First, it is a well-known result that under pure monopoly resource price starts higher and rises less rapidly. Under oligopoly, behavior can range from being similar to pure monopoly to being similar to perfect competition. For example, Salant (1976) shows that although the presence of a competitive fringe may constrain the ability of a dominant firm/cartel to diverge from a competitive pricing rule, the dominant firm will ensure that its reserves outlast the competition's so that it eventually becomes a pure monopolist. At the other extreme, even industries that have all the markings of imperfect competition, such as the U.S. copper industry prior to 1978, may actually not behave much differently from what

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[7] Gaudet (2007) provides an excellent, thorough survey of the effect of market structure on nonrenewable resource prices.

would be predicted by a competitive model (see Agostini 2006). In between these two extremes, the literature offers a rich set of results that can provide insights into the supply behavior of extractive firms. For example, Loury (1986) constructs a theory of "oil"igopoly and with it derives a number of predictions about supply behavior that are distinct from those predicted by a competitive equilibrium. Polasky (1992) tests these predictions and finds that the observed pattern of production for hundreds of U.S. oil companies in 1983 and 1984 and seventy-three countries from 1979 to 1989 is consistent with Loury's "oil"igopoly theory. Polasky's results show that the Hotelling model, recast within the context of oligopoly, provides useful insights into the understanding of observed extraction patterns for the oil industry across firms and nations. However, none of these models of imperfect competition helps to explain the empirical phenomenon that prices for nonrenewable resources have not been rising.

Pindyck (1978b), on the other hand, shows that the optimal pricing strategy for a cartel such as OPEC is *U*-shaped. Price is set high initially to exploit the short-run inelastic demand faced by the cartel. It is then allowed to decline, as demand becomes more elastic over time, until it eventually begins rising again to reflect the rising scarcity rent. Although Pindyck's results are consistent with the observed fall in oil prices after their peak in 1980, this is probably not a strategy OPEC could employ too many times. Salant (1979) analyzes a model in which a monopolist supplier of a nonrenewable resource faces potential competition from a backstop technology if price rises above a critical level. In this model, it is optimal for the monopolist to engage in what Salant calls a dynamic limit pricing strategy. This involves holding price constant over a possibly lengthy interval of time at a level just below the critical level, even though scarcity rent continues to rise. One can imagine that this is a pricing strategy a monopolist might employ to deter not only backstop supply, but also entry of higher cost sources of nonrenewable supply. Thus, this model may provide some rationale for nonincreasing resource prices.

Incorporating elements of market power into the Hotelling model has the potential to improve its ability to provide insight into the behavior of extractive firms. It also has the potential to provide insight into pricing strategies such as the two discussed above that might at first appear inconsistent with the predictions of the Hotelling Rule. Overall, however, one still has to appeal to the forces of technological change and unanticipated discoveries to reconcile the strong empirical evidence on nonrenewable resource price trends with theoretical predictions.

Direct Tests of the Hotelling Model

Looking for trends in market prices is an indirect way of testing the Hotelling Rule. After all, the Hotelling Rule is really about scarcity rent, and scarcity rent is just one among many factors that influences supply and price. A more direct test of the Hotelling Rule would be to compare the actual path of scarcity rent with the theoretical prediction. This is quite difficult, however, because scarcity rent is not usually observable and modern extensions of Hotelling's model have shown that the Hotelling Rule becomes much more complex when factors such as resource quality degradation are taken into account. Let me discuss the second issue first.

Impact of Resource Quality Degradation

The basic Hotelling model predicts that scarcity rent rises at the rate of interest. However, after incorporating the tendency for extraction costs to rise as the resource is depleted (the degradation effect), some recent papers have argued that scarcity rent eventually falls to zero at the point at which economic exhaustion occurs (Heal 1976; Solow and Wan 1976; Levhari and Liviatan 1977; Hanson 1980; and Chakravory and Roumasset 1990). Others argue that scarcity rent rises over time (Long 1979; and Krulce 1993), while still others argue that the path of scarcity rent is indeterminate and, hence, so is the predicted path of market price (Fisher 1981; and Farzin 1992). Livernois and Martin (2001) reconcile these apparently contradictory findings by showing that if the extraction cost function satisfies conventional regularity conditions, the path of scarcity rent is unambiguously nondecreasing.[8] Of course, there is no guarantee that extractive cost functions satisfy these regularity conditions in practice, so there is no guarantee that scarcity rent can be predicted to be monotonically rising. This complicates empirical testing, in the sense that the observation of either a rising or a falling scarcity rent would still not be sufficient evidence to support the Hotelling Rule. Instead, in order to control for degradation effects, it becomes necessary to estimate structural models that are based on an assumed cost function. Inevitably, this makes the test a joint test of the structural model and the Hotelling Rule.

Nonobservability of Scarcity Rent

The first issue—that scarcity rent is not usually observable—presents a more serious problem. Researchers have for the most part been forced to estimate the value of scarcity rent at each point in time by some indirect method. The estimated time series for scarcity rent is then tested to see if it conforms to the path predicted by the Hotelling Rule. Obviously, tests of this nature are only as good as the initial estimates of scarcity rent. In practice, it is difficult to distinguish scarcity rent from rents due to market power and short-run capacity constraints (Krautkraemer 1998), which of course reduces the credibility of any direct test of the Hotelling Rule in which scarcity rent is estimated.

Evidence from the Canadian Nickel Industry

The Canadian nickel industry has figured prominently in the empirical literature on the Hotelling Rule. Cairns (1981) used data for the Canadian nickel industry to estimate a value for scarcity rent. He assumed an exponential tonnage-grade model for the resource and a cost function that depends on grade. Cairns used the results of Levhari and Liviatan (1977), who show that, assuming the resource will never be physically exhausted, scarcity rent consists only of the degradation cost (the present-valued sum of all increases in future costs caused by a marginal degradation of the current stock of ore). Cairns found that, even with strong assumptions, scarcity rent is no more than 5 percent of the metal's value. This is perhaps not surprising given that known nickel reserves in Canada in the 1970s, as he noted, were of the order of 70 times the extraction rate.

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[8] Specifically, it must be jointly convex in its two arguments: the rate of extraction and the stock of remaining reserves.

Stollery (1983) argued that the nickel industry was ideal for testing the Hotelling Rule because world's nickel supply from the 1950s to 1970s was dominated by a single Canadian firm, the International Nickel Corporation (INCO), so that it was the unquestioned price leader. This made it possible "to study demand, costs, reserves and discovery rates of INCO alone for determination of world nickel prices without having to resort to a complex oligopoly model". Stollery (1983) estimated the demand curve facing INCO, from which he calculated marginal revenue, and a constant-elasticity-of-substitution (CES) cost function for extraction, from which he calculated marginal cost. Scarcity rent was calculated by subtracting the estimated marginal cost from marginal revenue for each year in the sample (1947–1974). Stollery concluded that scarcity rent, while positive, was a small fraction of output price, a result that is consistent with Cairns' (1981) results. However, a plot over time of his estimated scarcity rent shows it growing fairly steadily, suggesting that Stollery's results may well be consistent with the predicted Hotelling Rule path.

Although Stollery's estimated scarcity rent rose over time, so did the market price. In fact, Cairns (1986) noticed that the estimated scarcity rent seemed to be a fairly constant share of market price. This led him to suggest that Stollery's results were also consistent with a static monopoly-pricing rule under which price equals marginal cost plus a constant markup, a hypothesis neither Cairns (1985) nor Stollery (1985) was subsequently able to reject. Ellis and Halvorsen (2002) investigated this conjecture further. One of the main innovations in their paper was to develop a methodology that allowed them to identify what portion of the wedge between price and marginal cost is due to market power and what portion is due to scarcity rent. What they found was that there was a substantial wedge between price and marginal cost in the Canadian nickel industry, but that most of it was due to market power. In fact, their econometric results found a user cost of about the same magnitude as Cairns'. Using the same data, Lee (2007) estimates values for the scarcity rent for nickel that are consistent with those cited above. However, he finds that the path of his estimated scarcity rent is not consistent with what is predicted by the Hotelling Rule.

The evidence on the Canadian nickel industry seems to point to the conclusion that there is a positive scarcity rent but that it is small and, in fact, relatively insignificant compared to the rent that is due to INCO's market power. Although on balance the evidence does not clearly reject or support the Hotelling Rule, it does suggest that scarcity rent was not an empirically significant determinant of market price.

More Empirical Evidence Concerning Scarcity Rent

Farrow (1985) used proprietary monthly data from an underground mine from January 1975 to December 1981 to derive estimated monthly values for scarcity rent.[9] He then tested whether these estimated values obey the Hotelling Rule by running a regression of the change in scarcity rent on a number of explanatory variables, including scarcity rent. According to the Hotelling Rule, the percentage change in scarcity rent should equal the interest rate, after controlling for other factors such as the degradation effect. Therefore, the estimated value of the coefficient on scarcity rent in his regression should equal the interest rate. Although

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[9] More specifically, he estimated a cost function and used it to derive monthly predicted values for marginal cost, which in turn were subtracted from the market price

Farrow tried many variants of the model to capture the effects of various constraints and characteristics of the underground mine, he consistently estimated a negative coefficient value for the interest rate, a clear rejection of the Hotelling Rule.[10]

Young (1992) used panel data on fourteen Canadian copper mines to test the Hotelling model and found that the evidence "corroborates the findings of Farrow (1985) that when firm-level data are examined, they are not consistent with Hotelling's rule." Halvorsen and Smith (1991) estimate scarcity rent in a highly aggregated model of the Canadian metal mining industry and also strongly reject the Hotelling Rule.

Impact of Risk Adjustments

Gaudet and Howitt (1989); Gaudet and Khadr (1991); and Gaudet (2007) show that in the presence of risk, it is necessary to further refine the Hotelling Rule. Holding a mineral asset is risky, and therefore the equilibrium rate of return required by investors in order to hold the asset will include a risk premium. Whether the risk premium is positive or negative depends on how the return on holding the resource is correlated with other assets. Gaudet (2007) points out that it is theoretically possible that if the risk premium is sufficiently negative (because of a strong negative covariance between the rate of change of scarcity rent and the rate of change of consumption), the risk-adjusted Hotelling Rule could imply flat or even decreasing scarcity rent. Slade and Thille (1997) test a risk-adjusted Hotelling Rule using Young's (1992) panel data on fourteen Canadian copper mines. They note that the variance of the price of copper is nearly 100 times its mean, indicating that risk is clearly an important feature in that industry. They find that adjusting the Hotelling Rule for risk leads to improved results over those obtained by Young (1992). In fact, they are unable to reject the risk-adjusted Hotelling Rule; however, they caution readers not to view these results as confirmation of the Hotelling Rule because their statistical test has very little power to reject, and the degree of risk diversification implied by their estimates is too large. Nevertheless, the addition of risk to the Hotelling model clearly improved its empirical performance.

Young and Ryan (1996) also test a risk-adjusted Hotelling Rule but this time using industry-level data for lead, zinc, copper, and silver mining in Canada. Although they find plausible evidence for positive risk premia, it is "not sufficient to completely reconcile such a model with historical price and cost data." They attribute the weak results to problems in obtaining appropriate data.

An Empirical Test: Stumpage Prices for Old-Growth Forests

One serious weakness in all the empirical literature discussed above is the lack of data on scarcity rent. To address this weakness, Livernois, Thille, and Zhang (2006) use data on stumpage price bids for old-growth forests in the U.S. Pacific Northwest as a proxy for scarcity rent. Because these old-growth forests are several hundred years old, they are effectively a nonrenewable resource. Private logging firms bid for the right to harvest tracts of old-growth forestland at regularly scheduled public auctions. The winning bid, called the stumpage price, is what the winning firm is willing to pay per unit harvested As such, these

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[10] However, as Farrow notes, he actually is rejecting jointly the model used to estimate scarcity rent and the degradation effect along with the Hotelling Rule.

bids are a reasonable proxy for scarcity rent. Livernois, Thille, and Zhang (2006) develop and test a modified Hotelling Rule that accounts for the opportunity cost of land occupied by standing timber. According to this modified rule, stumpage prices should evolve over time in a predictable manner. The modified Hotelling Rule is the basis for the empirical test. The initial regression model used to test the Hotelling Rule is analogous to Farrow's (1985), in that the key coefficient should have an estimated value equal to the interest rate. Whereas Farrow obtained negative values for this coefficient using mineral data, the analysis of the old-growth timber data produces a value of 8.6 percent for the implied interest rate, which is a credible value. In further versions of the model, a number of approaches are used to represent the risk-adjusted discount rate, including the Capital Asset Pricing Model, but the Hotelling Rule still cannot be rejected. Unfortunately, the power of the tests is again low, which is probably due in large part to the high degree of volatility in the stumpage price data. Nevertheless, these results are by far the most favorable yet seen in the empirical literature on the Hotelling Rule.

Why does the Hotelling Rule perform empirically so much better for old-growth stumpage prices than for mineral commodities? The first and most obvious reason is that in the case of old-growth stumpage prices, direct observations are available and are good proxies for scarcity rent. There may be a second reason that has to do with the fact that for old-growth forests the expected stock of recoverable "reserves" and the expected quality of remaining "reserves" probably did not change much from the beginning to the end of the sample. In mining, firms are likely to be updating both of these expectations as they learn about their resource base, which means scarcity rent will be updated too. Without an ability to control for these kinds of revisions as learning takes place, the *ex post* empirical performance of the Hotelling Rule is likely to continue to be only moderately good at best.

In fact, this is the same conclusion reached by Swierzbinski and Mendelsohn (1989b). They model exploration as producing both information and discoveries, with information leading to revised expectations about the likely success of future exploration. They show that the forecasted mean rate of change in scarcity rent is given by the Hotelling Rule. However, the true or *ex post* mean rate of change typically differs from the Hotelling prediction due to the unanticipated changes in expectations caused by the arrival of information. On the basis of this theoretical result, Swierzbinski and Mendelsohn (1989b) argue that *ex post* tests of the Hotelling Rule are not likely to prove successful, but that *ex ante* tests that exploit the predictive power of the Hotelling Rule are likely to be more successful. This leads us to our next topic: a discussion of *ex ante* direct tests of the Hotelling Rule.

The Hotelling Valuation Principle

One testable implication of the basic Hotelling Rule is what Miller and Upton (1985a) termed the Hotelling Valuation Principle, which says that the *ex ante* market value of the reserves of a nonrenewable resource is predicted by the current net price multiplied by the amount of reserves. In the basic Hotelling model with a constant unit cost, profit in any period is just the net price multiplied by the quantity extracted. Since the present value of net price is constant over the life of the mine, the present value of total profit over the life of the mine is just the total reserves extracted multiplied by the current net price.

The elegance of the HVP is that only the current values of price and marginal cost are required to predict the market value of the stock of reserves, even though those reserves will be exploited over many years to come. Thus the HVP provides a simple and convenient method for valuing a firm's or a nation's stock of nonrenewable reserves, which makes it useful in Green National Income Accounting or for investors wanting to determine the market value of a firm's natural capital.

In principle, the HVP can be tested by regressing the observed market value of in situ reserves per unit on observed contemporaneous values of net price, followed by a test of the hypotheses that the intercept term is 0 and the estimated coefficient on net price is equal to 1. Miller and Upton (1985a) showed that the theoretical relationship between market value of reserves and net price becomes more complicated in a Hotelling model that has been augmented to allow for extraction costs that rise with the rate of extraction and resource depletion. The implication is that the estimated intercept term no longer needs to equal 0. However, the estimated coefficient on net price should still be equal to 1, and that remains the important hypothesis test. Since the prices at which in situ reserves change hands are rarely made public, Miller and Upton (1985a) calculate these values using published stock market prices for a sample of U.S. domestic oil- and gas-producing companies after making adjustments for the firms' nonresource assets and liabilities. They find that the estimated coefficient on net price is not statistically different from 1 and conclude that the HVP performs well by accounting for a significant portion of the observed variations in market values. For this reason, the Miller–Upton paper is often cited as the most successful test of the Hotelling Rule.

Subsequent research has produced less favorable results. For example, Watkins (1992) finds that the HVP significantly overestimates the observed values of oil and gas reserves. Even Miller and Upton (1985b), using an updated data set, find that the estimated coefficient on net price falls from about 0.9 in their first study to 0.5. Adelman (1993) argues that the evidence from a number of his studies on actual sales of reserves shows that the unit value of reserves fluctuates around a value of 0.5. He adds that a general rule of thumb among petroleum firms is that the "in-ground value of a developed reserve is one-third of wellhead price, or about one-half of price (net of operating costs, royalties and taxes)." Adelman concludes that, on the basis of the evidence, the "Hotelling Rule and the Hotelling Valuation Principle are thoroughly discredited."

Davis and Cairns (1999), on the other hand, show that it is not the Hotelling model per se that is discredited, but rather that in its highly simplified form it does not capture some of the critical physical constraints under which oil and gas extraction occur. They modify the basic Hotelling model to reflect that (a) the production rate of oil or gas is governed by reservoir pressure which tends to decline with cumulative production, (b) the market price of oil does not rise fast enough to make the producer's net price rise as rapidly as the discount rate, and (c) firms are faced with regulatory constraints on production rates. The authors then derive what they call a Hotelling-type valuation principle and conclude that current net price remains a sufficient statistic to calculate the unit value of reserves; however, they show that their modifications generate a coefficient on net price that is less than 1, and suggest that a value of 0.5 is implied by reasonable parameter values for the model.

The HVP has also been tested for nonfuel nonrenewable resources. Cairns and Davis (1998) use gold reserves transaction data and find that the intercept is 0, but the coefficient on net price is significantly less than 1 (about 0.7). They again attribute the failure of the HVP to its overly simplified model of the production process. They argue that firms have far less flexibility to adjust extraction rates up or down than is implied by the basic Hotelling Rule and develop a "reformulation of the Hotelling Valuation Principle" that takes some of the special characteristics of hard-rock mining into account. Their reformulated rule turns out to be consistent with the data.

One conclusion we can draw from the literature discussed above is that the simple HVP often overestimates the market value of reserves by as much as a factor of 2. The implication is that the simple HVP will overvalue a nation's nonrenewable resource assets in national income accounting. However, the case of old-growth timber may be an exception. Berck and Bentley (1997) use the HVP to estimate the "enhancement" to the value of remaining timber land that occurred as a result of the U.S. government's inclusion of a considerable stock of old-growth timber land in the Redwood National Park in California in 1968 and 1978. While Berck and Bentley did not formally test the HVP in this context, they were unable to reject parameter restrictions implied by the Hotelling Rule in their econometric model of supply and demand. This, combined with the favorable results in Livernois, Thille, and Zhang (2006), suggests that it may be more fruitful to use old-growth forestry data rather than mineral data to test the HVP.

Conclusions

The purpose of this article has been to evaluate the empirical significance of the Hotelling Rule by reviewing the evidence on the behavior of market prices over time, the evidence on the effects of technological change, direct tests on scarcity rent itself, and the performance of the HVP.

Based on the empirical evidence, I have found that overall one cannot conclude that the Hotelling Rule has been a significant force governing the evolution of observed price paths for nonrenewable resources. It appears that other factors, notably technological change, revisions to expectations regarding the resource base, and market structure, have had a more significant influence on the evolution of prices. On the other hand, nothing we have observed in the evolution of prices is inconsistent with the Hotelling Rule. But if the Hotelling Rule is only one among many supply-side factors that influences price, all kinds of price paths are possible. Only by controlling for these other supply factors do we have a credible chance of refuting or supporting the Hotelling Rule. This is an important though difficult area for further empirical research.

Direct tests of the Hotelling Rule to evaluate whether scarcity rent follows its predicted path have been mostly unsuccessful, with one or two exceptions. As I have argued, this is perhaps not surprising as *ex post* tests are not likely to be successful unless one is able to control for the revisions to expectations regarding the quantity and quality of the resource base in response to new information. The fact that *ex ante* tests have also been largely unsuccessful is a cause for concern. However, as Cairns and Davis (1998) point out, when we conduct these tests at the level of the individual mine or a small segment of the industry, the physical and technical constraints under which extraction occurs become critical. The existence of these constraints does not necessarily invalidate the conceptual message of the Hotelling

Rule, but does make it extremely difficult to uncover evidence that the Hotelling Rule is operating.

Finally, one can ask whether suppliers of nonrenewable resources really do make supply decisions in the way that is assumed in a Hotelling-type model. Pindyck (1981) asks whether other behavioral assumptions such as bounded rationality (which may imply the use of rules of thumb for making extraction and pricing decisions) or even myopic optimization would provide a better basis for explaining observed resource prices and supply behavior. Cairns (1986) says that mining firms do not make any effort to factor scarcity rent considerations into their determination of output and, if applicable, price. Rather, he argues, other considerations, such as fluctuating markets, technological change, and cost control, tend to dominate their thinking. Slade (1988) points out that "in the medium run (several decades) price uncertainty and volatility overwhelm any deterministic trends." Indeed, if one puts oneself in the shoes of a mine operator, factors such as extreme price volatility, the requirement to raise large amounts of capital, and the importance of delineating the ore body, for example, are probably far more immediate concerns than scarcity rent.

The empirical evidence seems to suggest that scarcity rent may actually have been the least important determinant of price so far. Yet the Hotelling Rule continues to be a central feature of models of nonrenewable resource markets in the literature. Does this mean that there has been a misplaced emphasis in the literature? I don't think so. The Hotelling Rule, or some variant of it, is a consequence of any model which assumes that mining firms think not just about the present but also about the future, and that they wish to maximize the value of their assets. Although mining firms may not be conscious of scarcity rent, at least not in the literal sense, that does not mean that rationality is an unreasonable behavioral assumption. In the end, however, the proof is in the pudding—or in the empirical testing. Unfortunately, the empirical evidence to date has not provided overwhelming support for the Hotelling Rule.

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