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Hotelling's Rule Repealed? An Examination of Exhaustible Resource Pricing

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Contrary to the predictions of economic theory, prices of important exhaustible resources have not appreciated in real terms during the past century. Possible explanations for the lack of a trend in prices, such as changes in demand, discoveries of new reserves, and technological change are explored in this article. Based on the evidence, it appears that theoretical models consistently have underestimated the price elasticity of supply of and demand for exhaustible resources. Despite increasing consumption, resource availability has increased as well, suggesting that pressure for rising real resource prices will continue to be suppressed.

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An important contribution of economics to public policy is in the area of intertemporal resource allocation—particularly in the case of the optimal depletion of exhaustible resources. Models ranging from very simple to highly-sophisticated treatments of the topic have provided important insights into how market forces often can address problems of growing scarcity without intervention by centralized authorities.

One illustration of this role was provided in the early 1970s with the publication of *Limits to Growth* (LTG).[1] Using computer simulations of trends in consumption, output, resources, and population growth, LTG projected growing shortages of key raw materials and a declining standard of living in the world economy. Those projections, however, ignored the endogeneity of prices. Rebuttals to LTG based on dynamic optimization models were able to evaluate the likelihood of the LTG outcomes and suggest a far more adaptive environment. Prices would rise as commodities become scarce, they argued, causing automatic shifts in consumption patterns.

The predictions generated by the dynamic optimization models have become increasingly important in economic policy formation. Growing familiarity with dynamic optimization techniques led to the widespread adoption in economic and forecasting models of many of the "arbitrage equations" that are generated in the intertemporal optimization literature. For example, following the oil price spikes in 1973-74 and 1979-80, predictions of future oil prices routinely have been based on the intuitively appealing arbitrage relationship often referred to as "Hotelling's rule," which states that prices of exhaustible resources should rise at the same rate as other financial assets. That is, the rate of price increase should equal the interest rate. Otherwise, commodity holders would not be indifferent between current and future sales, and hence, would withhold or accelerate current sales until the present value of the future price equaled the current price.

This assumption that oil prices would be determined by Hotelling's rule continues to be embedded in most dynamic economic forecasting models. Especially in long-term forecasting models, oil prices are assumed to rise faster than the general level of inflation because the real interest rate is positive.

This assumption, however, fails to correspond to experience. As discussed in this article, oil prices, as well as most other major mineral prices, have not followed the predicted path. Since the 1870s, these real resource prices have not had a noticeable trend, in contrast to the rising trend predicted by Hotelling's rule. Moreover, prices have been highly volatile, rather than stable as arbitrage relationships would suggest.

In both the LTG and Hotelling scenarios, the explicit exhaustibility of the resource is a central assumption. New discoveries and innovations can alter the period over which extraction and consumption occur, but the resource eventually is fully consumed. Consequently, both theories predict declining per capita wealth unless the economy can substitute other factors of production for the resource.

Historical data contradict this view, however. As discussed in this article, the issue of scarcity and exhaustibility of natural resources is questioned by the evidence: prices have not appreciated in real terms, consumption has risen, and known reserves have risen sharply for nearly all resources examined here.

The thrust of this article is to suggest that neither the LTG nor the Hotelling scenarios, as commonly expressed, are likely. Because of a consistent tendency to underestimate the response of technological progress and innovations to perceptions of scarcity, the models using Hotelling arbitrage equations will tend to underpredict resource availability and overpredict price increases. Moreover, the LTG predictions are unlikely because technological progress appears to occur at a sufficiently rapid pace to prevent growing scarcity.

In Section I, the simple Hotelling model and the resulting arbitrage equations are derived. Empirical evidence testing the arbitrage condition for copper, lead, iron, zinc, and petroleum is then presented in Section II. The evidence generally provides poor support for a Hotelling price path, indicating the absence of a trend and the presence of large unexplained errors. Several explanations for this failure are presented in Section III. Some of the most important causes—uncertainty about reserves and the rate of technological change, the properties of the extraction cost function, shifts in tastes, changes in market structure, and problems caused by imperfect information—are discussed.

Concluding remarks are presented in Section IV. Based on the information problems, uncertainty, and the empirical evidence presented in this article, Hotelling's rule appears to be a poor guide for projecting prices of exhaustible resources, and the LTG model provides a poor prediction of resource scarcity. Rather, the lack of a trend in real resource prices suggests that economic forces are working to encourage expanding resource availability.

I. Hotelling's Rule

Exhaustible resources have received special attention in the economics literature. A resource is said to be exhaustible if its current use in some way reduces a finite stock of future uses:

> If we ignore the act of extraction as a production activity, such a resource is among the class of non-produced goods (i.e., it is a primary commodity). But then, so is agricultural land, and we do not usually regard land as being exhaustible in the same way as fossil fuels are. The distinguishing feature of an exhaustible resource is that it is used up as an input in production and at the same time its undisturbed rate of growth is nil. In short, the intertemporal sum of the *services* provided by a given stock of an exhaustible resource is finite. Land, if carefully tilled, can in principle provide an unbounded sum of services over time. This is the difference.[2]

Exhaustible resources, therefore, can command a scarcity premium that grows over time, and unlike land, this growth does not depend on the growth of demand for the service, but rather, on the diminishing availability of the stock of services because of previous consumption. Any consumption of the resource should increase the scarcity of the resource and, hence, affect the value of future scarcity rents. Optimal depletion of an exhaustible resource, therefore, is a problem of intertemporal allocation.

The most influential approach to modeling intertemporal depletion of exhaustible resources is generally attributed to Hotelling (1931). Hotelling derived the path of optimal prices and consumption in a model that assumes that the objective of society is to maximize the present discounted value of consumption of a resource that has a fixed stock. In its simplest form, the Hotelling problem can be stated as follows:

$$\underset{c}{\text{maximize}} \quad \int_0^T e^{-\delta t}\, U(c(t))\, dt \qquad (1)$$

$$\text{subject to:} \quad \dot{R}(t) = -c(t) \qquad (2)$$

$$R(0) \geq \int_0^T c(t)dt \qquad (3)$$

$$R(t),\ c(t) \geq 0.^{3} \qquad (4)$$

where R is the level of remaining reserves, c is the consumption of the resource at time t, U(c) is the utility associated with consumption of the resource at time t (which is assumed equal to production, for simplicity), δ is the discount rate, and T is the (finite) date at which the resource is depleted. The problem is one of choosing an optimal consumption path, c(t), to yield the highest value to the agent subject to the constraints that production must always be positive and cumulative production cannot exceed the resource stock.

The fixed supply of the resource is the critical difference between exhaustible resources and other commodities produced at constant cost. Because the initial stock of resources is in fixed supply, a scarcity premium can be captured by the resource owner. Hence, as long as the scarcity is sufficiently apparent, prices can exceed production costs throughout the period of its consumption.

The mathematical solution of (1) - (4) involves straightforward application of the calculus of variations, and is available in a variety of sources [Hotelling (1931), Dasgupta and Heal (1974), Stiglitz (1974), and Schmidt (1984)]. It can be demonstrated that the arbitrage equation determining intertemporal allocations is:

$$\dot{U}'(t)/U'(t) = \delta. \tag{5}$$

The solution affirms that resource use is optimal when the marginal utility of consumption rises at the agent's discount rate. When this occurs, the present value of the marginal utility of the last unit is the same in each time period, and because the marginal utility of consumption is assumed to be inversely related to consumption, no opportunity for arbitrage would remain.

In a competitive system, the marginal utility of consumption is proportional with the observed price for the commodity. Substituting the resource price for U'(t), the marginal utility of consumption, yields what has come to be known as "Hotelling's rule":

$$\dot{P}(t)/P(t) = \delta \tag{6}$$

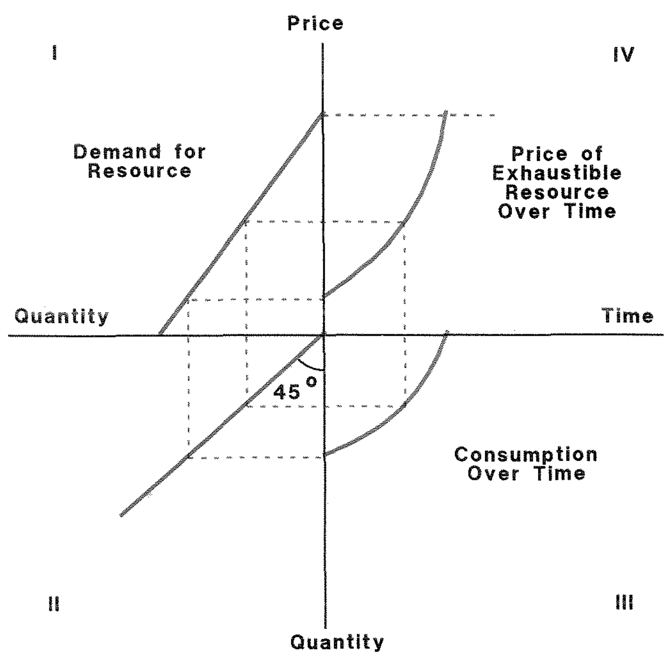
Equation (6) predicts that real prices will rise at the rate of time preference, which is often proxied by the observed rate of interest.[4]

The logic behind this rule is difficult to contest. Producers with perfect foresight and no holding or production costs should be indifferent between current and future production as long as the resource appreciates at the same rate that the proceeds from current production would earn if invested in other assets. If prices grow at a faster rate, arbitrage opportunities exist that would encourage reduced current production, because the returns to sales in the future would have a higher present value. This response would reduce the rate of price appreciation.

The solution to the problem can be seen graphically in Figure 1, a four-quadrant depiction of the optimal depletion problem [Herfindahl (1967)]. As demonstrated in Figure 1, an optimal price path can be determined by using the arbitrage equation to define the rate of change between periods, in conjunction with the resource constraint, which makes it possible to determine the starting price level.

The first quadrant depicts the demand curve for the resource at a point in time. For simplicity, it is assumed that demand is stationary; that is, the demand curve does not shift over time. The second quadrant simply maps the consumption at a particular point in time from the demand curve in quadrant I to its cumulative consumption in quadrant III. Quadrant III keeps track of resource use over time. The area bounded by the consumption path and the axes determines whether the chosen price and consumption paths violate the resource constraint. This area equals total consumption over time, and cannot exceed the available reserves of the resource. The fourth quadrant maps the price path described by Hotelling's rule.

Figure 1
The Optimal Depletion of an Exhaustible Resource



To determine the optimal path, an initial starting price is chosen in quadrant IV. Then, given the resulting price path in IV and the demand curve in quadrant I, it is possible to trace out the implied consumption path in quadrant III. The cumulative consumption resulting from the price path can be compared to the resource stock available. If the implied consumption exceeds the available stock, the starting price is raised in quadrant I and the exercise is repeated. When the starting price and resulting price path exactly exhaust the available resource at the time when the price reaches a level at which demand is choked off, the path is optimal.

The particular resource model developed above uses highly restrictive assumptions. In particular, it assumes constant demand, no extraction costs, known reserves, and no technological change. As discussed later in this article, more complicated depletion models have relaxed some of these assumptions. These enhancements modify the optimal price path and make the relationship expressed in equation (6) more complex, but the results continue to predict a positive relationship between price appreciation and interest rates. In other words, the model described in (1)-(4) is an abstraction, but the central prediction—that real prices should rise over time—is independent of many of these assumptions.

II. Empirical Evidence

In contrast to the theoretical predictions, however, Charts 1a-1e show that the real prices of copper, lead, iron, zinc, and petroleum have been highly volatile, but have not exhibited a significant trend over the period from 1870 to 1986. Current real prices for many of these minerals are at the levels of 100 years ago. None of the minerals has exhibited the real appreciation that would be predicted by a simple model.

Interestingly, the only mineral that visually demonstrates a rising real price is iron, which has little scarcity rent attributed to the resource. Also, the commodities that demonstrated some significant trend in the early 1980s have seen a sharp reversal. Copper is shown with a declining price since 1970, but the recent surge in copper prices (not shown) has raised the price close to the historical average price. Similarly, the explosion in oil prices in 1979-80 now has been reversed, although the current level remains above the historical average of $12.81 (in 1985 dollars).

One test of the Hotelling relationship between prices and the rate of interest follows directly from equation (6). As shown by Feige and Geweke (1979), a simple test of the relationship is to estimate the following equation:

$$\ln(P_{t+1}/P_t) = \alpha + \beta r_t + \epsilon_t, \qquad (7)$$

where r is the rate of return on alternative investments and P is the price of the resource. The Hotelling model would imply that $\alpha = 0$ and $\beta = 1$.

A joint test of this hypothesis for copper, iron, lead, zinc, and petroleum is presented in Table 1.[5] The annual data cover the period 1870 to 1986.[6] As shown in the table, there is little support for the Hotelling model. Interest rate coefficients are negative and in all cases not significantly different from zero. Furthermore, as shown in Table 1, the Durbin-Watson statistic suggests that there is little autocor-

Table 1
Testing Hotelling's Rule

Commodity	Intercept	Rate	adj. R^2	F-test*	DW	Eqn. F**
Iron	0.0838	−1.4866	−.004	1.54	2.27	0.94
	(1.10)	(−0.84)				
Copper	0.0932	−1.8386	−.002	1.78	1.73	0.72
	(1.10)	(−0.95)				
Lead	0.1020	−2.0221	.002	1.95	1.91	0.89
	(1.23)	(−1.06)				
Zinc	0.0775	−1.3853	−.013	0.27	3.21	0.13
	(0.41)	(−0.32)				
Petroleum	0.0686	−1.2341	−.009	1.21	2.06	0.45
	(0.77)	(−0.60)				

* Testing the joint hypothesis that the intercept equals zero and the coefficient on the interest rate equals one.

** Testing the joint hypothesis that both the intercept and interest rate coefficients are zero.

Chart 1A
Real Copper Prices
(1985 Dollars)

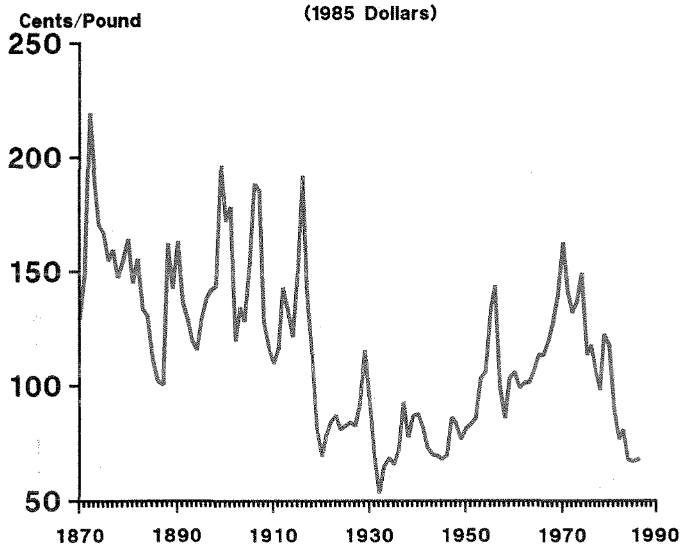


Chart 1B
Real Iron Prices
(1985 Dollars)

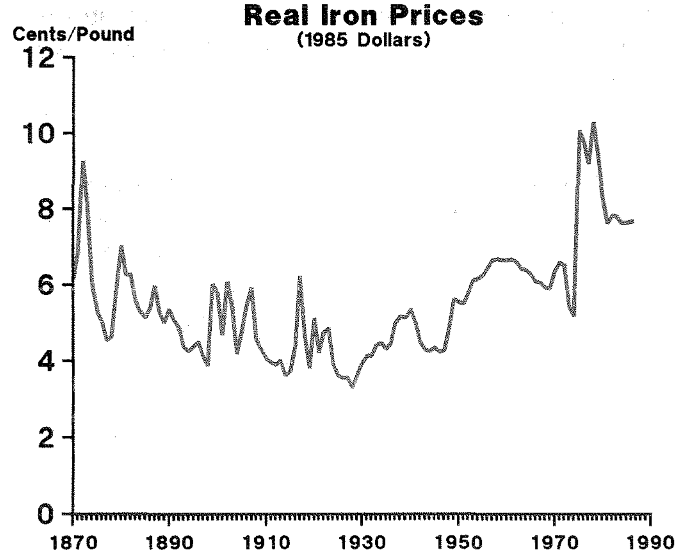


Chart 1C
Real Lead Prices
(1985 Dollars)

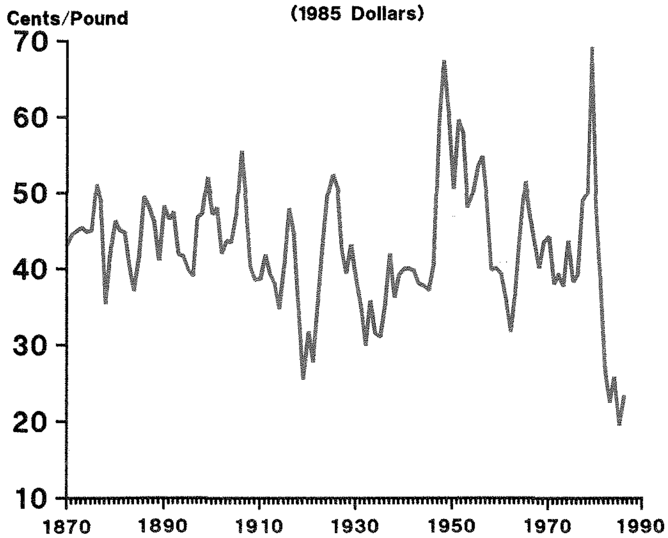


Chart 1D
Real Oil Prices
(1985 Dollars)

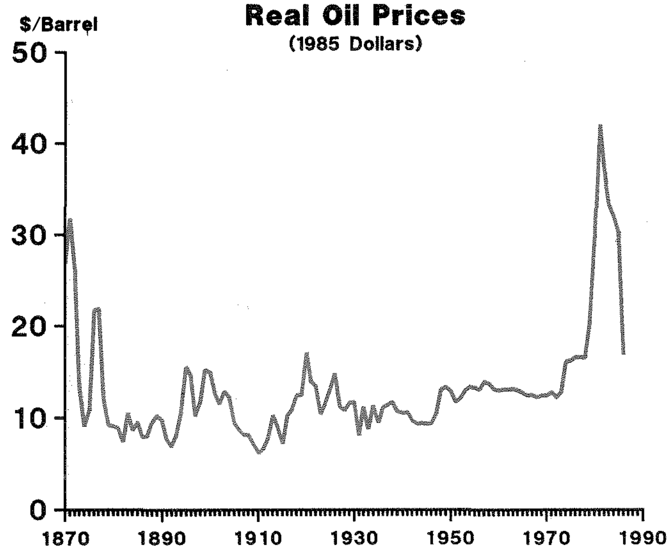
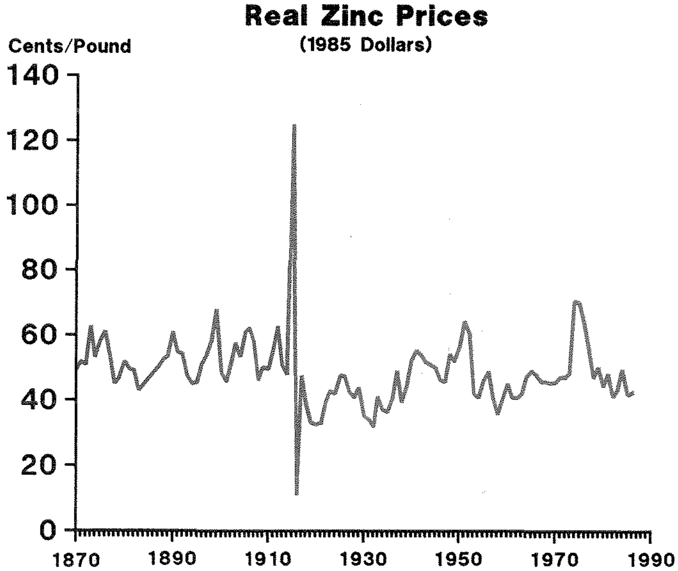


Chart 1E
Real Zinc Prices
(1985 Dollars)



relation in the errors for commodities other than zinc, indicating a lack of even short-term price trends. The lack of a significant constant term in the regressions also is consistent with a trendless process.

Similar to Feige and Geweke's findings, however, the joint hypothesis $\alpha = 0$ and $\beta = 1$ cannot be rejected. Given the theoretically incorrect signs on the coefficients, this evidence provides extremely weak support for the hypothesis. A more likely interpretation of the results would point to the low signal-to-noise ratio. The hypothesis cannot be rejected simply because the unexplained error swamps the explained variation. In fact, as shown by the second F statistic in the table, which tests the hypothesis that both coefficients are not significantly different from zero, those restrictions also cannot be rejected. Consequently, little confidence can be placed in the model's reliability.

Because of the naive specification of the model, it is not surprising that the data fail to confirm the Hotelling model. Clearly, other factors are important in shaping and explaining short-term movements. Smith (1981) and Heal and Barrow (1980), for example, have presented evidence demonstrating that arbitrage-based models that include several lagged price and interest rate terms have lower forecast errors than a simple univariate time series representation for some minerals (copper and lead in the Smith study).[7] However, the "best" specification was not consistent among models, and the best specification often was rejected as unacceptable because the coefficient on the interest rate term was negative.[8]

With more sophisticated versions of the Hotelling framework, optimal price paths need not be exponential. For example, as discussed in greater detail in the next section, optimal price paths can be shown to have U-shaped structures, given certain extraction cost schedules. In virtually all of these models, however, an upward trend would have been predicted in recent data.

Some have argued that the trendless nature of real resource prices does not violate the Hotelling model since *ex post* risk-free real interest rates have been close to zero over much of the period under study. However, even with zero real interest rates, the coefficient on the interest rate variable should not be negative in these models. Moreover, estimates of a model with *ex post* real interest rates and the *ex post* inflation rate as the explanatory variables (along with a constant) yielded similar results. Only in the case of lead was the inflation or interest rate variable significant, and in that case, the coefficients were both negative.

III. Factors Preventing Price Appreciation

The failure of Hotelling's rule to predict price behavior has been attributed to the restrictiveness of many of its underlying assumptions and may not reflect any inconsistency with intertemporal optimization.[9] In this section, several of these assumptions—no extraction costs, known reserves, no technological change, and static demand—are examined. This analysis suggests that the reason prices have failed to follow Hotelling's path is that technological innovations affecting both supply and demand consistently have made resource constraints less binding. At the same time, changes in market structure, along with these unexpected and abrupt changes in supply and demand, have contributed to the volatility of resource prices.

Extraction costs

A number of researchers have attempted to provide deterministic explanations for deviations from the Hotelling price path based on the properties of the extraction cost function [Solow and Wan (1976), Hanson (1980), and Roumasset, Isaak, and Fesharaki (1983)]. They argue that, holding technology and knowledge of the stock of the resource constant, the most easily accessible sources of the resource will be exploited first. This suggests that extraction costs should rise over time, and this will affect the resource price path [Dasgupta and Heal (1974, 1979)]. However, as demonstrated in this section, extraction costs alone—unless changed unexpectedly—do not explain why prices have not risen.

Inclusion of extraction costs in the optimal depletion problem results in a modified rule that requires prices net of marginal extraction costs to rise at the rate of interest:

$$\dot{P}(t) = r\,[P(t) - b(t)] \qquad (8)$$

where b is the marginal extraction cost at time t, and r is the discount rate [Hanson (1980)]. Rearranging terms, (8) can be expressed as follows:

$$\dot{P}(t)/P(t) = r\,[1 - b(t)/P(t)]. \qquad (9)$$

As can be seen by inspecting (9), if b(t) is zero, the arbitrage equation reverts to that shown in equation (6), assuming that $r = \delta$. If b is a positive constant, on the other hand, prices will grow at a slower rate than if extraction costs were zero, but the rate will rise over time, and eventually will approach the growth rate observed in (6).[10] Furthermore, if marginal extraction costs rise over time, the growth rate of prices remains below that in the zero extraction case, and the rate of growth in prices can slow to nearly zero if costs rise faster than prices. Finally, if b(t) is discontinuous, involving discrete changes in extraction costs as the extractor moves to a lower grade of the resource, it is possible for the price path to exhibit periods of accelerating increase and periods of slowing growth.[11]

Most importantly in these models, however, prices should rise monotonically if the stock of reserves is known and fixed. As shown in (9), the only time prices fall (that is, grow at a negative rate) is when resource prices fall below marginal extraction costs, at which time production should not occur.

The price path can be U-shaped, however, if the model is further expanded to treat exploration and production costs separately, and if the initial reserve stock is small [Pindyck (1978)]. If production costs of the resource depend on both the exploration and the development of a resource, marginal costs could fall in initial stages as the resource is discovered and stocks of proven reserves grow. In this case, the decline in production costs exceeds the rise in exploration costs. In later stages, if costs of exploration continue to increase, costs would rise, forcing the price to rise as well.

Empirically, the impact of changes in extraction costs is especially difficult to isolate because of the lack of cost data. Evidence taken from various mineral census years is presented in Table 2. As can be seen in the table, real extraction costs of all minerals experienced step changes following World War II and in the 1970s.[12] Furthermore, the breakdown of costs between labor, on the one hand, and supplies and machinery, on the other, indicate a rapidly growing capital component to the cost function, suggesting exploitation of grades that are more difficult to extract.

However, these data reflect average unit costs, and do not indicate the path of marginal extraction costs. Furthermore, in the case of oil, the post-1973 observations include the effect of the rapid increase in oil prices and resulting development of high-cost energy supplies outside of OPEC. This high-cost development could not be construed as optimal development from a global standpoint, however, given that marginal extraction costs in the Middle East remained far below the marginal cost of the high-cost sources, and the Middle East had surplus capacity.

Similarly, rising commodity prices toward the end of the 1970s led to a sharp increase in exploration for other minerals, such as copper. Because of the high prices, marginal extraction costs rose significantly. When prices fell, the industry retrenched and closed down or modernized the higher-cost facilities. In recent years, prices again have risen, but unit costs are considerably lower because of the efficiency gains achieved when prices fell. Consequently, when examining extraction costs, it is important to distinguish temporarily high costs during periods of rapid price appreciation—when cost control is less apparent—and equilibrium situations where costs are closer to long-run equilibrium levels.

Other evidence by researchers finds limited support at best to indicate that rising extraction costs explain the

Table 2
Mineral Production and Extraction Costs

Year	Production Index	Costs: Payroll	Costs: Supplies & Machinery	Costs: Total	Unit Cost
	(1967 = 100)	(Millions of 1967 Dollars)			
1919	45	2044.8	1082.5	3127.3	69.5
1939	68	2959.7	1896.7	4856.4	71.4
1954	72	3961.1	7026.3	10987.4	152.6
1958	78	3963.0	7950.3	11913.3	152.7
1963	89	3960.9	9496.3	13457.1	151.2
1967	100	4187.0	10576.0	14763.0	147.6
1972	108	5261.1	12497.1	17758.2	164.0
1977	118	6780.1	23727.6	30507.7	259.0
1982	126	9568.0	36651.2	46219.2	366.5

Sources: Production data: Board of Governors, Federal Reserve System.
Cost data: Bureau of the Census, U.S. Department of Commerce.

trends in resource prices. Roumasset, *et. al* (1983) provide some evidence relating the oil price increases of the 1970s to rising extraction costs. Unfortunately, the marginal extraction costs they use are for U.S. producers, while the appropriate marginal extraction cost may be OPEC producers. Moreover, their results also fail to explain the pattern of prices over a longer period of time.

Rather, the absence of a rising trend in resource prices suggests two factors may be at work. First, technological change has offset rising extraction costs by developing more efficient extraction methods. Consequently, costs have been held down by productivity gains. Second, unexpected discoveries of reserves or technological progress in exploration have provided lower marginal cost extraction opportunities. Examples of discoveries of oil in Alaska, Mexico, and Columbia in the past 20 years suggest that this phenomenon is important.

Uncertain reserves

Changes in extraction and exploration technology all affect the size of the stock of proven, or extractible, reserves. This uncertainty about the reserve base contrasts with another underlying assumption in the Hotelling model. Constant real appreciation in exhaustible resource prices is derived in this model because the reserve stock is known with certainty (as are the demand function and extraction costs). In practice, however, reserves are not known with certainty and have increased dramatically over time, often in large, discrete leaps.

Table 3 presents estimates of reserves for several minerals for 1950 and 1974. Despite continued extraction and production of the minerals, reserves in 1974 were several times larger. In the case of asbestos and bauxite, for example, additions to reserves (new discoveries and extension of previously discovered reserves) were 11 to 17 times the known reserve bases in 1950. A similar pattern is found in petroleum and natural gas reserves, where additions to world reserves have tended to outstrip production.

The effect of uncertain reserves on the optimal depletion path has been examined in a number of studies [Arrow and Chang (1982), Pindyck (1980), Dasgupta and Heal (1979)]. An unanticipated shock to reserves can cause a shift among optimal paths. A sudden, unanticipated increase in proven reserves causes the price trajectory to fall to assure full resource exhaustion. Observed prices in these models fall sharply when the discovery is made.

In addition to unanticipated shocks to the reserve base, a number of these models address the impact of endogenous exploration behavior on the resource price path. As shown by Arrow and Chang (1982), exploration tends to accelerate as the stock of known reserves declines and the price of the resource rises. With major new discoveries, exploration tends to slow until scarcity again becomes important. The implied price path, therefore, is one that rises and falls, with little apparent trend.

As pointed out by Pindyck (1980), uncertainty about the stock of reserves is consistent with observed price behavior, although such uncertainty does not fully explain that behavior. Clearly, reserve shocks have played an important role in preventing the LTG scenario from occurring by consistently raising the size of the resource stock. The timing of reserve discoveries and shifts in price trajectories, however, do not coincide precisely as the theory would predict. Announcements of large new deposits have sometimes caused prices to move, but often there is little immediate response. For example, the major oil discoveries by Mexico in the mid-1970s may have contributed to pressure on OPEC in the mid-1980s, but those discoveries seemingly had little effect on prices in the mid-1970s.

In any case, the frequency with which shocks to the reserve base have occurred—either because of luck or because of the endogenous response of enhanced exploration activity—raises an important issue regarding the

Table 3
Changes in Selected Mineral Reserves, 1950–74
(Metric Tons)

Mineral	1950 Reserves	1974 Reserves	Reserve Additions as a Percent of of 1950 Reserves*
Asbestos	3.9×10^7	8.7×10^7	281
Bauxite	1.4×10^9	1.6×10^{10}	1103
Chromium	1.0×10^8	1.7×10^9	1696
Copper	1.0×10^8	3.9×10^8	403
Iron	1.9×10^{10}	8.8×10^{10}	401
Lead	4.0×10^7	1.5×10^8	433
Manganese	5.0×10^8	1.9×10^9	313
Nickel	1.4×10^7	4.4×10^7	281
Tin	6.0×10^6	1.0×10^7	144
Zinc	7.0×10^7	1.2×10^8	210

Source: John E. Tilton, *The Future of Nonfuel Minerals* (Washington, D.C.: Brookings Institute, 1977), selected minerals from Table 2-2, page 10.

* Additions to reserves are calculated by adding cumulative production of the mineral between 1950 and 1974 to the difference between 1974 and 1950 reserve estimates. The reported figures are additions to reserves divided by 1950 reserves, in percentage terms.

degree to which these resources really are exhaustible. The steady rise in reserves, despite growing demand (see Charts 2a-2e, which depict a steady upward trend in consumption), may argue for decreasing scarcity value of the resource over time. If these resources are not exhaustible in practice, the failure of Hotelling's rule to predict trends in resource prices would not be surprising.

Uncertainty in demand

Technical change affecting the demand for a resource also may be an important factor in the observed failure of the Hotelling model. A key assumption of the model is that demand for the resource is known and predictable. In reality, however, dramatic changes in use patterns, the availability of alternatives, and variations in resource use intensity have caused frequent shifts in the demand for the resources. For example, the discovery of semiconductors and silicon chips significantly reduced the demand for copper wiring. Increased energy efficiency in automobiles, including substitution of aluminum and plastic for steel, had a direct impact on iron and petroleum demand.

These technological shocks result, in part, from a direct response to perceived shortages—reflected in rising prices—and from spin-off discoveries in other applications. In the short-run, most resource demand is highly inelastic. Over the longer-term, however, substitutes tend to develop that allow much greater substitutability. Often, the emergence of the substitutes leads to relatively sudden shifts in demand when the product appears, typically exceeding expectations of resource producers.[13] When these shifts occur, the expected consumption path is altered, and the optimal depletion path changes.

Such changes in demand can lead to consistent errors in the estimation of demand. Adjustments by producers to those errors then can affect the observed price path for resources. (See the accompanying Box.)

Relatively simple models of resource depletion have been developed for the case where alternative technologies exist. In the simplest form [Dasgupta and Heal (1979)], a "backstop" technology is assumed to exist in perfectly elastic supply at some price. The only effect of this modification is to affect the starting value of the arbitrage equation.

A more complicated version of the process [Kamien and Schwartz (1978)] considers the optimal depletion problem when the alternative technology is endogenously determined. The extractor must then choose a price and production schedule that maximizes profits taking into account the effect that the price level will have on encouraging alternatives. This approach, however, continues to predict monotonically rising resource prices.

A model of endogenous alternative production can generate observed price declines, however, if the assumption of complete information is relaxed. As is the case with unanticipated additions to reserves and sudden changes in technology or final demand, information limitations can lead to unstable price paths. If, for example, development of an alternative is characterized by high initial investment and low marginal costs, a sudden increase in resource prices can cause a large increase in the availability of the alternative. This increase, in turn, can force prices to fall.

Models in which prices can fall depend on the existence of uncertainty. Prices fall because supply or demand conditions change in a way the resource producer cannot anticipate. Presumably, if the producer could anticipate all responses to a given price path, the producer would follow an extraction path that would avoid these price declines. Otherwise, the arbitrage condition would be violated.

The fact that prices do fall suggests that these information problems are significant. Furthermore, the information problems are not merely the result of luck, but also because information is not often fully disseminated to the affected parties. If the supply of and demand for the resource depends on the actions of many agents, and the involved agents do not have all the information on how the other agents will react, this imperfect information can lead to unstable prices.

Consider, for example, the case of alternative production [Schmidt (1988)]. If the extractor and the alternative producer are different agents, and information is proprietary, so that: a) the extractor does not know the nature of the relationship between resource price levels and changes in the price level on the future supply of alternatives; and b) the alternative producer does not know with certainty the desired price path of the extractor, unstable pricing can be generated.

Consider the simplest case: no extraction costs, known reserves, and constant total demand for the resource and the alternative, which is a perfect substitute. The resource extractor will seek to find the price path that maximizes the present value of extraction rents, taking into account the *expected* effect of the selected price path on the supply of the alternative.

The alternative producer is assumed to choose current investment in research and development to bring the substitute on line at some future period. The optimal investment level is determined, among other factors, by the substitute producer's expectations of resource price appreciation.

In both cases, expectations are based on imperfect information. Furthermore, it is typically the case that the gestation period of an alternative product is considerable.

Chart 2A
Copper Consumption

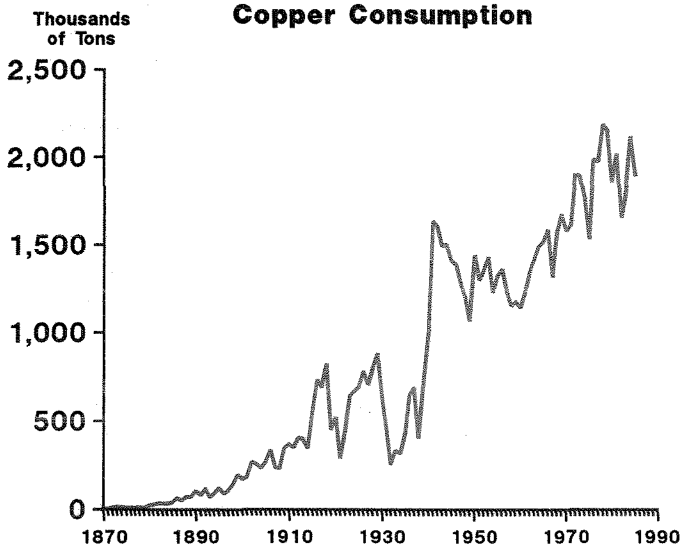


Chart 2B
Iron Consumption

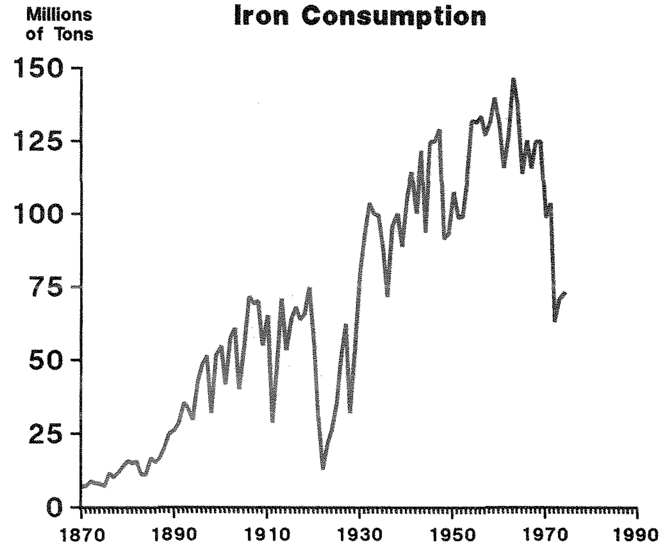


Chart 2C
Lead Consumption

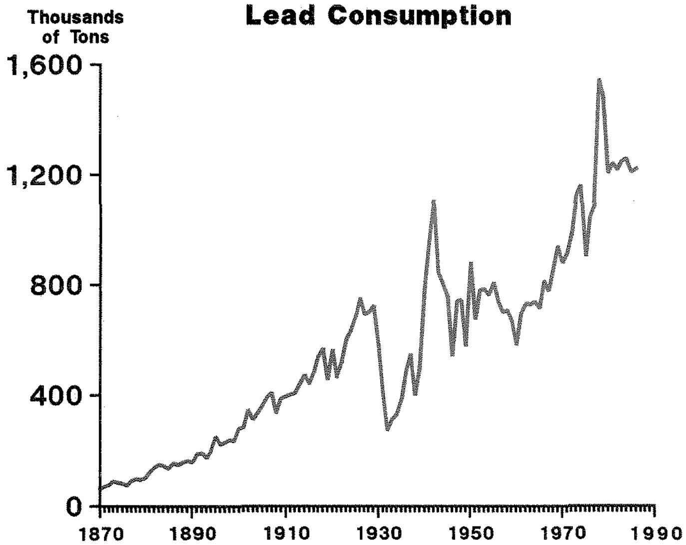


Chart 2D
Oil Consumption

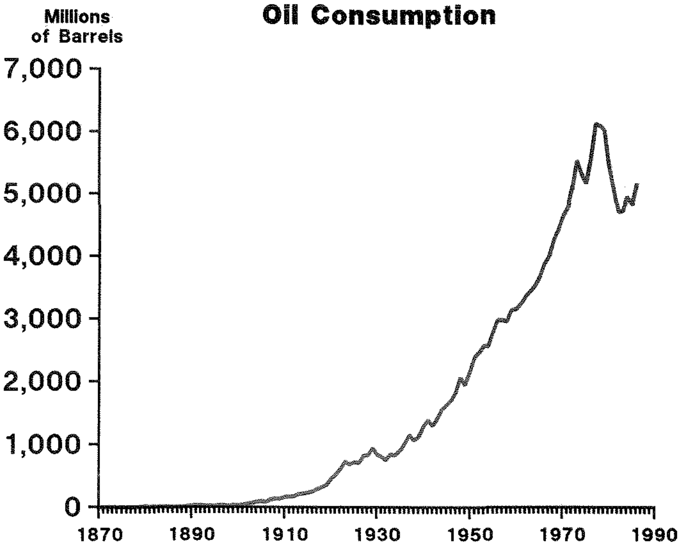
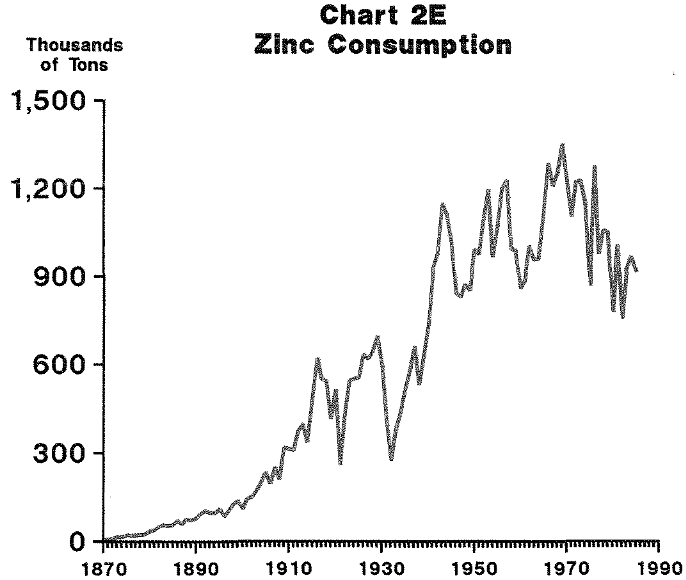


Chart 2E
Zinc Consumption



Consequently, it is possible for the extractor to underestimate the response of the alternative producer, and choose a higher initial price.[14] In this case, the response of alternative production will exceed that expected by the extractor in future periods, forcing the extractor to shift to a lower optimal price path. This shift to a lower price path would appear as a sudden drop in observed prices.

Similarly, sudden price declines might convince the alternative producer that prices will remain low, and lead to sharp cutbacks in development activities. Such a cutback would then result in lower alternative production in the future than would be expected by the extractor, possibly leading the extractor to shift to a higher price path in the future.

Unless the agents learn the true nature of each other's optimization solution—which may entail acquiring proprietary information—the process of observed price shocks can continue indefinitely. This phenomenon explains, in part, why extractive industries also frequently are major investors in the development of substitute products in order to internalize these informational externalities. For example, synfuels are developed by oil companies. Nevertheless, some substitutes inevitably emerge from non-extractive sources, surprising the market (for example, the replacement of copper by fiber optics).

Moreover, miscalculations of demand elasticities may cause extractors to raise prices so rapidly as to encourage the development of alternatives that have high fixed costs, but competitive marginal costs. The sharp increase in oil prices led to major new investments in production capability outside OPEC, where marginal production costs after drilling were low enough to continue production even after prices fell. Furthermore, the price spike was sufficiently dramatic to encourage enormous investments

Forecast Errors Caused by Misspecified Models

Incorrect forecasts of demand may be partially the result of misreading short term trends and extrapolations based on the assumption of exponential growth. Estimates of demand often are based on logarithmic specifications that explicitly force exponential growth forecasts. Population growth, which is exponential, is often used as a justification for this approach.

In practice, however, growth of consumption for many commodities has had a linear growth trend. As shown in Charts 2a–2e, the growth of consumption in the five commodities appears to have a slight exponential growth rate, but that rate is relatively small. To demonstrate the effect of this functional form misspecification, evidence on ten-year-ahead forecast errors is presented in the table for linear and exponential forecast models using rolling forecasting horizons. The models are each assumed to be re-estimated each year using the last 30 years of data and then projected forward 10 years.

Results in the table suggest a strong bias towards overestimation in the exponential specifications compared to the projections of the linear model. Forecast errors made using an exponential model consistently were larger than those made by linear projections. On average, mean absolute forecast errors were 3.5 times larger in the exponential model than in the linear version. In all cases except the linear model for petroleum, the models over-estimated demand.

Demand miscalculations could occur systematically if the model is not adjusted to reflect this pattern. In fact, in the case of electricity demand forecasts, this pattern of projecting what should be a linear process with an exponential function apparently has been repeated frequently.*

*A discussion of this phenomenon is presented in Schmidt (1987), pp. 22-23.

Estimates of Consumption Trends: Comparison of Linear and Exponential Models
(Percent)

	Linear Model		Exponential Model	
Commodity	Mean Error	St. Dev.	Mean Error	St. Dev.
Iron	−23.4	87.1	−77.3	133.0
Copper	−1.5	49.5	−47.3	84.3
Lead	−2.3	38.5	−16.0	50.1
Petroleum	29.1	25.5	−33.7	55.1
Zinc	−3.0	37.3	−37.1	58.7

Note: Mean absolute forecast errors and standard deviations are calculated from a time series of ten-year-ahead forecast errors from linear and exponential models, each of which contain time and a constant as the explanatory variables. The models were reestimated each period using 30 prior years of observations, and the 10-year-ahead forecast was obtained and compared to the observed value.

in energy-efficient equipment and structure—investments that were not reversed when oil prices fell.

Consequently, the lack of perfect information among agents and the slow nature of adjustment can lead to a series of price fluctuations. Moreover, elimination of these shocks through learning often is not possible because the technology changes over time, resulting in new substitute producers with different production functions.

Market Power

Finally, a number of researchers have suggested that changes in the institutional structure of resource markets help to explain short-term movements in resource prices. Many important exhaustible resources are not sold in competitive markets. In particular, tin and petroleum are produced in cartelized market environments, and other minerals largely are owned and produced by state-owned enterprises that may have different objectives than those embedded in the Hotelling model.

Beginning with Hotelling (1931), economists have compared the implications for extraction and prices in competitive and monopolistic markets [Dasgupta and Heal (1974, 1979), Stiglitz (1974), Hnyilicza and Pindyck (1976), and Pindyck (1978)]. Researchers have found the production and price paths under the two market structures to be quite different. If marginal extraction costs are constant, monopolists will choose a price path that allows marginal revenues, rather than prices, to rise at the discount rate. Such a price path will tend to have higher initial prices and slower appreciation, leading to depletion over a longer period of time compared to the price path of a competitive producer.

This difference in optimal pricing patterns may explain part of the observed price behavior for some of the resources. For example, oil extraction has been characterized by major institutional changes. In the pre-World War II period, oil production was highly competitive in the United States—so much so, that the Governor of Texas called out the national guard to halt "cutthroat" competition in 1933, which had driven prices as low as ten cents per barrel. Beginning in 1933, prices were stabilized (and held virtually constant over long periods of time) by the prorationing policies of the Texas Railroad Commission. Production levels of Texas producers were set so as to meet refiner demand at prices then prevalent. This power waned in 1973 as imports became the marginal supply, and pricing since 1973 has reflected frequent shifts in the cartel unity of OPEC.

Similarly, a buyer's cartel has dominated the tin market for decades. Prices have risen and fallen over time with the cohesiveness of the cartel. Other industries also have had important structural changes as the market shares of government-controlled production have changed. In the case of copper, market shares have fluctuated sharply be tween U.S.producers (which produce in accordance with profit maximization goals) and Latin American producers (which produce to maximize foreign exchange). As the market shares change, the different objectives of the producing groups force changes in the optimal price path. Furthermore, competition for market share has at times forced production capacity to be idled as excessive supplies are dumped on the market, reducing world prices.

In cases such as these, where market institutions shift frequently, the price path can be expected to be discontinuous. Shifts in institutions reflect changes in underlying goals, changes in discount rates as different players become market-makers, and differing degrees of monopoly power. At each transition point, optimal price paths (optimal from the perspective of the dominant market participants) shift, and prices shift abruptly from the old path to the new path. In the cases of oil and copper, shifts in cartel cohesion have had immediate short-term effects on the direction of prices.

IV. Conclusions

Examination of exhaustible resource price data over the past century leads to a simple conclusion. Even with the enormous sociological, political, technological, and economic changes of the past 115 years, real prices of important exhaustible resources have not increased significantly. Certainly, those prices have at times risen or fallen sharply. But if one were attempting to forecast prices in the future, this historical behavior would nudge the forecaster toward a prediction of little future appreciation in real prices.

Does this mean that the dire consequences of resource exhaustion spelled out in LTG will occur? After all, one argument against the LTG model was the economic rationale that prices would rise and allow a gradual shift away from the resource, avoiding major disruptions. If prices do not rise, what forces are available to shift production and consumption patterns prior to the emergence of shortages?

Results of this study suggest that the corrective forces attributed to the pricing mechanism remain viable and have allowed consumption patterns to change in a nondisruptive fashion. Rather than projecting a gloomy decline in standards of living as we run out of resources, the interpretation in this article argues for the best of both worlds. Not only is the LTG scenario unlikely, but so are the price increases associated with the Hotelling scenario.

Rather, the trendless nature of real resource prices over the past 115 years suggests that the Hotelling and LTG approaches seriously underestimated the ability of agents to substitute other resources and develop alternatives.

Shifts in consumption, changes in reserves caused by new discoveries or gains in extractive technology, technological change that affects the output mix and production function of the economy, and shifting market power of cartels all have the effect of changing the optimal depletion trajectory. Moreover, growing reserves even with rising consumption, also brings into question the degree of scarcity that truly should be attributed to these resources.

The Hotelling model predicts a rising price path when reserves do not grow, alternative technologies do not exist, and demand does not change. But history would suggest that these conditions always will change. Moreover, rising prices in the short run seem to have a larger effect on the supply of alternatives than we generally expect, given our current state of knowledge and technology.

ENDNOTES

1. Meadows, Meadows, Randers, and Behrens (1972).

2. Dasgupta and Heal (1979), p. 153

3. A "dot" above a variable indicates the rate of change.

4. Prices and interest rates are usually expressed in real terms in the theory. A similar relationship (including that tested in Section III) exists between nominal prices and nominal interest rates.

5. Similar results can be demonstrated for a wide variety of other minerals.

6. Data for the estimation for 1870-1973 were taken from *Natural Resource Commodities—A Century of Statistics*, Robert S. Manthy, Johns Hopkins University Press (1978). Data for 1973-1986 were constructed using the methodology described by Manthy from more recent publications of the original sources. The interest rate is based on railroad bonds for the early part of the series, and based on Moody's Aaa corporate bonds in more recent years.

7. Smith, in particular, experimented with interest rates of differing maturities, but found that the term of the interest rate had little impact on the general relationship to price appreciation.

8. Smith (1981), p. 110.

9. Other studies that have attempted less direct tests of the theory have found mixed results for some implications of the Hotelling model in the data. Farrow (1985), using data from mining firms, found that the *in situ* value of the resource did not follow a time path consistent with the theory. On the other hand, Miller and Upton (1985) found some support for the theory by examining cross-sectional evidence of the stock market value of U.S. domestic oil and gas firms. Schmidt (1984) also found evidence that exploration activity was consistent with a Hotelling model, with drilling responding to expected real price appreciation.

10. Note that the limit of $\dot{b}(t)/P(t)$ is zero as $t \rightarrow \infty$, if $r > 0$.

11. See Hanson (1980) for a proof of this property.

12. The more recent data contrast with the findings of Barnett and Morse (1963), who found that extraction costs fell for almost all extractive products between 1870 and 1957.

13. This sequence of events characterized the pattern of oil prices in the 1979-86 period. Prices rose sharply in 1979-80, causing major investments in energy-saving technologies and the development of other sources of energy. As these sources emerged, the demand for OPEC oil diminished rapidly, leading to a sharp price decline over the 1982-86 period.

14. The producer also might choose this path if the gestation period is long and the producer's discount rate is high. In that case, the producer might attempt to capture short-term higher profits by exploiting the inelastic short-run demand, even though that action reduces future profits.

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