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Nonrenewable Resource Scarcity

JEFFREY A. KRAUTKRAEMER¹

"Contemplation of the world's disappearing supplies of minerals, forests, and other exhaustible assets had led to demands for regulation of their exploitation. The feeling that these products are now too cheap for the good of future generations, that they are being selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed wastefully has given rise to the conservation movement."

Harold Hotelling (1931)

1. Introduction

THE OPENING SENTENCES of Hotelling's seminal article on the economics of nonrenewable resource extraction highlight the recurring theme of the possible overexploitation of those resources. In the nineteenth century, W. Stanley Jevons was concerned about the effect of the increasing cost of coal supply on the British economy as low cost coal deposits were depleted. The Conservation Movement at the last turn of the century also was concerned with the depletion of coal reserves and other natural resources. Concern over nonrenewable resources after World War II led to the formation of the Paley Commission in 1952 and its charge to "... inquire 'into all major aspects of the problem of assuring an adequate supply of production materials

for our long-range needs and to make recommendations which will assist ... in formulating a comprehensive policy on such materials' " (Harold Barnett and Chandler Morse 1963). The long-term availability of fossil fuels, particularly petroleum, was the focus of concern about nonrenewable resource scarcity in the 1970s. More recent years have seen a greater emphasis on the environmental impacts of nonrenewable resource consumption.

Hotelling's formal analysis of nonrenewable resource depletion generates some basic implications for how the finite availability of a nonrenewable resource affects the resource price and extraction paths. The economic intuition behind these implications is relatively straightforward. A stock of a nonrenewable asset can be viewed as an asset that generates returns over time. An important opportunity cost of the current extraction and consumption of a unit of the resource is that there is less to extract and consume in the future. A mining firm that seeks to maximize the present value of profit takes this cost of

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resource depletion into account when making its current extraction decision: at the margin, the value of extraction from the resource stock—the resource price less the marginal extraction cost—should equal the value of not extracting from the resource stock—the marginal opportunity cost of depletion. This opportunity cost of depletion is known by a variety of terms: user cost, to reflect the cost of decreasing the future availability of the resource; *in situ* value, to reflect the marginal value of the resource stock in place; and resource rent, to reflect the difference between price and marginal extraction cost.

Asset market equilibrium requires the rate of return to holding the nonrenewable resource stock to equal the rate of return to other assets. In the basic Hotelling model, there is a known, finite quantity of a homogeneous resource, and extraction cost is independent of the remaining stock.² In this case, the return to a nonrenewable resource asset consists entirely of the appreciation of its *in situ* value, and market equilibrium requires the *in situ* value to increase at the rate of interest. This implication has become known as “Hotelling’s rule”: a concise, summary statement of nonrenewable resource theory. In the case of zero marginal extraction cost, the price of the resource equals the *in situ* value and so the resource price also would increase at the rate of interest. More generally, positive extraction costs imply resource price paths that increase at less than the rate of interest. The basic Hotelling model also has implications for the time path of extraction: with a stationary de-

mand curve, extraction decreases as the resource price increases over time. An increase in the rate of interest implies a more rapid increase in *in situ* value and this requires a lower initial *in situ* value and more rapid depletion of the initial resource stock.

For the most part, the implications of this basic Hotelling model have not been consistent with empirical studies of nonrenewable resource prices and *in situ* values. There has not been a persistent increase in nonrenewable resource prices over the last 125 years, but rather fluctuations around time trends whose direction can depend upon the time period selected as a vantage point. Of course, it is the *in situ* value of the resource stock, rather than the resource price itself, that the model implies will be increasing over time, but empirical studies of the dynamic behavior of *in situ* values also have failed to provide empirical support for the basic Hotelling extraction model.

Finite availability is not the only factor that significantly affects nonrenewable resource supply, and some implications of the basic Hotelling model are fundamentally altered when more complex and realistic features are included. The basic Hotelling model assumes a known stock of a resource of homogeneous quality and that the extraction technology does not change over time. In fact, nonrenewable resource stocks are not known with certainty, and exploration for new deposits, as well as further development of existing deposits, is an important feature of minerals industries. Moreover, since the outcome of exploration and development activities cannot be fully anticipated, expectations about the future value of the resource stock can be revised in response to specific exploration outcomes. Revised expectations about future value can alter the equilibrium resource price

² It also is implicitly assumed that the resource is not durable; that is, extraction and consumption of the resource makes it unavailable for future use. Some minerals, like gold and silver, are durable in some of their uses and can be recycled. This can delay the impact of finite availability on the resource price.

and extraction paths. Minerals industries are capital intensive, and the timing and size of investments in extractive capital are functions of the anticipated price path and the cost of capital. Once in place, it may be very costly to adjust extractive capacity in order to change the extraction rate in response to a change in the resource price path. As a result, the short-run supply of a nonrenewable resource may be quite inelastic, and changes in market demand will be resolved with price changes rather than quantity changes. This can generate volatile short- and intermediate-term price cycles around long-term trends. Moreover, since the cost of extractive capital increases with an increase in the rate of interest, it is no longer necessary that an increase in the rate of interest implies more rapid depletion.

This paper reviews some of the issues addressed in the literature on nonrenewable resource scarcity in the last 15–20 years. The next section presents a basic Hotelling model and establishes the basic implications of finite availability for intertemporal allocation. Extensions of the basic model that capture some other key features of nonrenewable resources, including exploration, capital investment, and heterogeneous ore quality, and how these theoretical extensions alter the implications of the basic Hotelling model are examined in Section 3. Empirical analyses of the implications of the Hotelling model are reviewed in Section 4. Given the persistent recurrence of concern about nonrenewable resource scarcity, Section 5 examines measures of nonrenewable resource scarcity and the empirical evidence for the time trends of those measures. Section 6 then examines the implications of nonrenewable resource scarcity for economic growth in the context of a neoclassical growth framework. The technological conditions necessary

for sustainable economic growth and a prescriptive rule for sustainability are discussed. This section also discusses some key criticisms of the neoclassical growth framework that have been raised in the sustainability literature. The section concludes with a discussion of incorporating nonrenewable resource depletion into the national income accounts in order to provide a more reliable measure of sustainable income.

2. The Basic Hotelling Model of Nonrenewable Resource Scarcity

The Hotelling model examines the intertemporal allocation of a known, finite stock of a nonrenewable resource. The decision maker chooses a time path for resource extraction, denoted $q(t)$, that maximizes the present value of the stream of net benefits from extraction, subject to the constraint that cumulative extraction is no greater than the initial resource endowment, denoted S_0 . If gross benefits are denoted by $B(q(t), S(t))$, and extraction costs are denoted by $C(q(t), S(t))$, where $S(t)$ denotes the remaining stock, then the optimal control formulation of the problem is to choose $q(t)$ to maximize:

$$\int_0^{\infty} e^{-\delta t} [B(q(t), S(t)) - C(q(t), S(t))] dt, \quad (1)$$

subject to:

$$\begin{aligned} \dot{S}(t) &= -q(t), \\ S(t) &\geq 0, \quad q(t) \geq 0, \quad S(0) = S_0, \end{aligned} \quad (2)$$

where δ denotes the rate of discount.

Letting $\lambda(t)$ denote the co-state variable for the resource stock, the current value Hamiltonian for this problem is:

$$\begin{aligned} H(q(t), \lambda(t)) &= B(q(t), S(t)) \\ &\quad - C(q(t), S(t)) - \lambda(t)q(t), \end{aligned} \quad (3)$$

where the co-state variable, $\lambda(t)$, has the economic interpretation of the current

value shadow price of the resource stock—its *in situ* value or user cost—at time t . The first order necessary conditions include static and dynamic efficiency conditions and a transversality condition. The static efficiency condition is:

$$\frac{\partial H}{\partial q} = B_q(q, S) - C_q(q, S) - \lambda = 0, \quad (4)$$

where the time argument is implicit and where $B_q(q, S)$ denotes $\partial B / \partial \theta$, etc. This condition requires that at each point in time, the marginal benefit from extracting the resource equals the marginal cost of extraction, including the user cost of depleting the resource stock, λ . Letting $\dot{\lambda}(t)$ denote the time derivative of user cost, the dynamic efficiency condition is:

$$\dot{\lambda} = \delta \lambda - \frac{\partial H}{\partial S} = \delta \lambda - B_s(q, S) + C_s(q, S), \quad (5)$$

or

$$\frac{\dot{\lambda}}{\lambda} + \frac{B_s(q, S) - C_s(q, S)}{\lambda} = \delta, \quad (6)$$

where B_s and C_s denote the derivatives of the benefit and cost functions with respect to the remaining resource stock. These derivatives can be non-zero if there are environmental amenities associated with nonexploited resource stocks or if the extraction cost increases as the resource stock is depleted. Dynamic efficiency requires the rate of return to holding the resource stock—the sum of the capital gain and the marginal net benefit generated by the resource stock—to equal the rate of discount. The familiar Hotelling rule that the shadow price of the resource stock should increase at the rate of discount, $\dot{\lambda}/\lambda = \delta$, is obtained from the dynamic efficiency condition when there are no stock effects; that is, $B_s = C_s = 0$. The transversality condition requires the present value of the value of the resource stock—the *in situ* value times the resource stock—be equal to zero at the

terminal time. Thus, either the resource stock is exhausted, or the present value of the terminal *in situ* value is zero. The transversality condition is needed to determine the initial value of *in situ* value.

The implications for the resource price path can be derived under specific assumptions about the benefit and cost functions. From the viewpoint of welfare maximization, the benefit function is the area under the demand curve so the marginal benefit of extraction, B_q , is the resource price, denoted by P . When marginal extraction cost is zero, the price of the extracted resource equals user cost and so the resource price increases at the rate of discount. The dynamic behavior of the resource price is more complicated when marginal extraction cost is positive. Assuming extraction cost is proportional to the extraction rate, $C_q = \gamma$ and differentiating the static efficiency condition with respect to time gives:

$$\frac{\dot{P}(t)}{P(t)} = \delta \left[1 - \frac{\gamma}{P(t)} \right] + \frac{\dot{\gamma}}{P(t)}, \quad (7)$$

where $\dot{\gamma}$ is the (exogenous) time derivative of marginal extraction cost. The rate of change in the resource price can be written as a weighted average of the discount rate and the rate of change in marginal cost with the weights given by the ratio of marginal cost to price:

$$\frac{\dot{P}(t)}{P(t)} = (1 - \theta)\delta + \theta \frac{\dot{\gamma}}{\gamma}, \quad (8)$$

where $\theta = \gamma/P(t)$.

When marginal extraction cost, C_q , is constant over time ($\dot{\gamma} = 0$), the rate of increase in the resource price is positive but less than the rate of discount. The resource price can be decreasing over a time interval if technological change lowers marginal extraction cost rapidly enough and marginal cost is close to price, which it can be at the beginning

of an extraction horizon. However, since the relative weight on the discount rate increases as *in situ* value increases and marginal cost decreases, the rate of price increase becomes larger and eventually must be positive. Consequently, technological progress that lowers marginal extraction cost over time can result in a U-shaped price path with the extracted resource price declining over some initial interval and then increasing as the effect of finite availability overtakes the effect of declining extraction cost. Such a U-shaped price path is consistent with observed prices for several minerals over the period 1870–1978 (Margaret Slade 1982b).

The resource price path also is more complicated when there are stock effects—that is, either benefits or costs are a function of the remaining resource stock. On the benefit side, depletion of the resource stock may result in the permanent loss of resource amenities—the recreational, scientific, and aesthetic services generated by preserved natural environments. On the cost side, it may become more costly to extract a given quantity of the resource as the stock is depleted; for example, ore must be lifted from greater depths, or well pressure declines as an oil reserve is depleted. In the case of a stock effect on the cost side, the dynamic efficiency condition (equation 5) implies:

$$\lambda(\tau) = \bar{\lambda} + \int_{\tau}^{\infty} e^{-\delta(t-\tau)} C_s(q(t), S(t)) dt, \quad (9)$$

where $\bar{\lambda} = \lim_{t \rightarrow \infty} e^{-\delta t} \lambda(t)$ is the present value user cost associated with the finite availability of the resource and often is referred to as the Hotelling rent. The transversality condition implies $\bar{\lambda} = 0$ if the resource stock is not exhausted at the end of the time horizon. The second term on the right-hand side of equation (9) is the differential rent portion of user cost, sometimes referred to as a Ri-

cardian stock rent.³ In this case, even the rate of increase in *in situ* value is less than the discount rate. With a stock effect, it is possible that extraction cost becomes great enough that it is optimal to stop extraction before the resource stock is exhausted; in this case, $\bar{\lambda} = 0$ and the user cost is composed of Ricardian stock rent only. This can occur if there is a “choke price” for the nonrenewable resource—that is, a price above which the quantity demanded is zero. Such a choke price occurs when the resource is not essential for production, perhaps because of the availability of a backstop technology.

The basic efficiency conditions combined with the transversality condition can be used to examine the effect of the rate of discount on the extraction and price paths. The rate of change in resource price is directly related to the discount rate so a lower rate of discount implies a less rapid increase in price. For a stationary demand structure, this implies that a lower rate of discount leads to greater cumulative extraction along price paths that begin at the same initial price. Since cumulative extraction is limited by the initial endowment, this implies the initial price must be greater when the rate of discount is lower. Consequently a lower rate of discount shifts extraction from the present to the future and a higher rate of discount shifts extraction from the future to the present. As will be seen later, the effect of the rate of discount on the extraction path becomes more complicated when capital is an input for extraction.

3. Theoretical Extensions of the Basic Hotelling Model

Even in fairly simple extraction models, the time paths for the resource

³ There also can be a Ricardian flow rent if marginal extraction cost increases with the rate of extraction.

price and *in situ* value can be more complicated than the basic Hotelling rule implies. The possible price paths become even more diverse when exploration, capital investment, and ore quality selection are taken into account.

3.1 *Exploration*

The basic Hotelling model assumes a known available resource stock, when, in fact, the ultimate availability of the resource depends upon the outcome of exploration activities. For many nonrenewable resources over many time periods, the discovery of additional deposits has exceeded consumption so that reserves have actually increased. For example, U.S. oil reserves increased from 13 billion barrels in 1930 to 20 billion barrels in 1990, while production in that interval was 124 billion barrels (Morris Adelman 1993). Similarly, world reserves of aluminum, copper, lead, nickel, petroleum, and zinc were greater in 1989 than in 1970 (Wilfred Beckerman 1996). The focus of this section is on how exploration and discovery alter the basic Hotelling implications.

The discovery of new reserves through exploration and development alters the equation of motion governing the time derivative of the resource stock (equation 2). If $e(t)$ denotes exploration activity and $D(e(t))$ denotes reserves discovered through exploration, then equation (2) becomes $\dot{S}(t) = D(e(t)) - q(t)$, where D is a random variable if exploration outcomes are uncertain. Uncertainty about exploration outcomes also can be introduced in a discrete fashion—i.e., exploration in a particular area results in the discovery of an increment of reserves with some positive probability. When exploration opportunities are finite, an additional state variable for remaining exploration opportunities is needed and exploration opportunities are a nonrenewable re-

source. Exploration activity enters the net benefit function negatively when exploration is costly. The optimal level of exploration activity balances the expected marginal benefit of exploration, which includes the value of additional reserves, with the marginal cost of exploration, including the user cost of depleting exploration opportunities. In addition to augmenting reserves, exploration activity can provide information that revises expectations about future exploration outcomes and so it can alter the entire resource price and extraction paths.

When exploration outcomes are certain, exploration is akin to the development of known but undeveloped reserves. One motivation for exploration before all known deposits are exhausted is that the discovery of new deposits may lower extraction cost. This occurs, for example, when there is a stock effect in the aggregate extraction cost function so that development of new reserves lowers the cost of extraction from existing reserves (Frederick Peterson 1978; Robert Pindyck 1978). If the initial reserve level is relatively small, then initial extraction cost is high, which implies the initial extraction rate is low and the initial price is high. The high initial price and extraction cost encourages exploration in order to acquire reserves to lower extraction cost and so reserves are increasing early in the time horizon. Reserve accumulation affords greater extraction through lower extraction cost and it reduces the incentive to explore; both these effects eventually reduce reserve accumulation, and extraction begins to decline as reserves decline. With a stationary demand curve, the resource price moves in the opposite direction of extraction and so the resource price path can be U-shaped (Pindyck 1978).

An aggregate cost function can be

written as a decreasing function of aggregate reserves if the resource stock is known with certainty and low cost deposits are exploited first. However, low cost deposits aren't necessarily discovered first, and new reserve discoveries would not affect extraction cost at existing reserves in different locations. When the discovery of deposits is random, the aggregate extraction cost function cannot be described by the reserve stock alone (Joseph Swierzbinski and Robert Mendelsohn 1989a). In the absence of stock effects for an individual deposit, the resource price is always increasing. However, if there are depletion effects within individual deposits, then rising costs at existing deposits are an incentive to develop new deposits, and it still is possible to have a U-shaped price path (John Livernois and Russell Uhler 1987).

The effect of uncertain exploration on the resource price and extraction paths varies with the nature of that uncertainty. Uncertainty does not necessarily alter the Hotelling rule with respect to the expected price path. With risk neutrality and a continuous time stochastic process, uncertainty about exploration outcomes affects the level but not the expected rate of change in the resource price path. The Hotelling rule with a stock effect is followed unless cumulative extraction reduces the variance of the expected level of reserves. As might be expected, the effect of exploration that reduces uncertainty depends upon the shape of the extraction cost function. The expected rate of change in the resource price is less (greater) than the rate of interest if extraction cost is a convex (concave) function of reserves (Pindyck 1980).

An alternative formulation of uncertain exploration outcomes is to have resource deposits occur in discrete locations and distributed randomly across a

finite area. A common assumption is that there is a Poisson distribution with a known and unchanging probability of discovery within a given area. When exploration cost is proportional to exploration activity, exploration and discovery occur in episodes with intervals of no exploration between those episodes. During an interval with no exploration, in situ value increases at the rate of interest. At the points in time when exploration occurs, there are discrete jumps up or down in the price path, depending upon the exploration outcome. Consequently, the resource price path follows a "saw-tooth" pattern (Partha Dasgupta and Geoffrey Heal 1979; Kenneth Arrow and Sheldon Chang 1982).⁴ The actual price path can have a downward trend over some time periods, depending upon the actual outcome of exploration activity. However, with a finite land area for exploration, exploration opportunities are a nonrenewable resource that earns a scarcity rent that imparts an upward trend in the expected price path. As unexplored land becomes more scarce, the likelihood that the resource price will increase because of unsuccessful exploration also increases. Consequently, there is a stronger upward trend in the resource price as exploration opportunities approach exhaustion (Pierre Lasserre 1984).⁵

In addition to augmenting reserves, exploration provides new information that can revise expectations about the future value of the resource stock and generate new expected time paths for

⁴ While exploration does not generally occur in strictly discrete episodes, it does vary with the resource price and large discoveries do put significant downward pressure on price.

⁵ With unlimited exploration opportunities, the resource price increases at the rate of discount between exploration episodes but the upward pressure on the price trend is missing (Sudhakar Deshmukh and Stanley Pliska 1980).

resource price and extraction. For example, exploration may provide information that causes a firm to revise its estimate of the probability of successful exploration. In this case, a variety of patterns is possible for the realized price path, including a generally downward trend (Nguyen Van Quyen 1991). The distinction between the expected price path at a particular point in time and the observed price path is an important one. While the Hotelling rule can give the best forecast for the expected rate of change in the price path, the arrival of previously unanticipated information can alter the resource price, extraction, and exploration paths so that the actual price path deviates systematically from the Hotelling rule (Swierzbinski and Mendelsohn 1989b). This has an important implication for empirical tests of the Hotelling rule: the observed time paths for the resource price and *in situ* value may represent a combination of the initial portion of many different expected price paths rather than outcomes along one fully anticipated price path. Swierzbinski and Mendelsohn (1989b) note that empirical tests of the Hotelling rule based on expected price paths, such as the Hotelling valuation principle (discussed below), have tended to perform somewhat better than empirical tests that rely on time series data.

A final implication of exploration activity is that discovery cost can provide some empirical insight into the dynamic behavior of *in situ* value. Since exploration is costly but produces valuable reserves, one would expect exploration to occur up to the point where the marginal cost of exploration is equal to the expected marginal value of discovered reserves. Indeed, the expected marginal value of reserves should equal the expected marginal cost of exploration plus the shadow price of exploration oppor-

tunities less the covariance between the exploration outcome and the marginal value of reserves (Lasserre 1985b).

3.2 *Capital Investment and Capacity Constraints*

Mineral extraction and production are capital intensive activities. By itself, this does not necessarily distinguish minerals production from the production of many other commodities. However, the extraction of a mineral commodity over time is limited by the finite availability of the resource in the deposit. Consequently, the initial resource stock is an important factor in determining the size of the initial capital investment, particularly if capital is non-malleable. Once installed, the initial capital investment can constrain the extraction path over some portion of the firm's time horizon, and the cost of changing extractive capacity affects the firm's ability to change output in response to unanticipated price changes. Thus, capital investment complicates extraction models and can alter some of the basic Hotelling implications.

For example, when capital is an extractive input, extraction cost varies with the interest rate since the interest rate is the cost of capital. Consequently, the equilibrium resource price path can be a function of changes in the interest rate as well as the level of the interest rate. This is consistent with empirical findings discussed in Section 4 below. Moreover, since a higher interest rate decreases the incentive to use capital, it can decrease rather than increase initial extraction whether or not capital is malleable. A higher interest rate implies a lower *in situ* value but also more costly extraction. If the initial resource stock is relatively large, then *in situ* value is relatively small, and the impact of a higher interest rate on the cost of capital outweighs its impact on *in situ* value,

and depletion is less rapid rather than more rapid (Y. Hossein Farzin 1984). A higher interest rate may also increase the cost of capital investment in a back-stop technology which increases the choke price for the nonrenewable resource, resulting in less rapid extraction. Since there is an inverse relationship between user cost and the interest rate, there is a non-monotonic relationship between the interest rate and initial extraction. A lower interest rate increases conservation if the interest rate is low (when user cost is high and capital cost is low) but decreases conservation when the interest rate is high (user cost is low and capital cost is high) (Gabriel Lozada 1993). An empirical study of the relevant parameters suggests that the effect of the interest rate on processed mineral output is the opposite of that implied by the standard Hotelling model, at least for several minerals with high capital intensity in the processing sector (Kenneth Stollery 1991).

The malleability of capital investment is another important consideration for the selection of an extraction path. For example, if the present value of the resource price is expected to decrease over time, then generally one would expect the firm's output also to decrease over time. The firm would reduce its capital input as extraction declines, unless capital is nonmalleable.⁶ The firm takes the nonmalleability of capital into account when the initial investment is made and the initial capital investment is lower than if capital is malleable; this can constrain the firm's output early in the time horizon. Depending upon the nature of the extraction cost function, this capacity constraint can be strictly binding and the firm's output is constant, rather than

decreasing, at the chosen capacity even though the present value of the resource price is decreasing (Harry Campbell 1980).⁷ This has important empirical implications for the measurement of user cost. When the constraint is binding, the difference between price and marginal extraction cost will reflect the shadow price of capital in addition to in situ value. The spread between price and marginal cost is constant while output is constant; in situ value increases at the rate of interest, but this is offset by an equal decrease in the shadow price of capital. Estimating in situ value by the difference between price and marginal extraction cost will overestimate in situ value and underestimate the rate of increase in in situ value.

The capital intensity of mineral production, the long time periods necessary for large investment projects, and the nonmalleability of capital reduce the extractive firm's ability to adjust the rate of extraction when the resource price changes. Unanticipated resource price increases may induce capital investments that take several years to become productive, and subsequent output may remain relatively constant even as price changes. In the case of identical firms with identical deposits, the resource price is constant, rather than decreasing, over an initial time period (Lozada 1993). With heterogeneous deposits of different sizes and nonmalleable capital investment, the resource price can be declining at first and there can be short-run price fluctuations around the trend (Robert Cairns and Lasserre 1986). Cycles

⁶ A putty-clay hypothesis for capital investment was not rejected by a sample of 40 investment decisions by 15 mining firms (Lasserre 1985a).

⁷ If the capital input affects the productivity of other inputs, then extraction costs may go to infinity asymptotically as the capacity constraint is approached (Tracy Lewis 1985). In this case, the constraint is never strictly binding and output will decline through time, although the rate of decline may not be very large.

around a price trend also occur if extractive capacity adjusts to price changes with a lag. The empirically estimated average price cycle length for seven nonfuel minerals over the period 1870 to 1978 ranges from 10 to 13 years, which is longer than cycles implied by inventory adjustments or business cycles (Slade 1982a). Long price cycles can complicate the interpretation of resource price data as indicators of resource scarcity.

3.3 *Ore Quality*

Nonrenewable resources generally occur in deposits of various grades. Incorporating heterogeneous deposits into the Hotelling model requires a separate state variable and user cost variable for each deposit. In the simplest case where ore quality varies across deposits but is homogeneous within a deposit, marginal extraction cost is constant, and the demand function is stationary, the optimal extraction pattern requires exploiting the deposits in strict sequence from high quality ore to low quality ore. Alternatively, deposits could be described in terms of metal extraction cost and then the sequence is from low cost to high cost. The user cost for a lower cost deposit is greater than the user cost for a higher cost deposit. At the time of transition from one deposit to the next most costly deposit, the marginal extraction cost plus user cost is the same at each deposit. This implies that the resource price rises at less than the rate of interest so the outcome is similar to a model with increasing extraction cost as the resource stock declines (James Sweeney 1993). Simultaneous extraction from different deposits can be optimal when marginal extraction cost at a deposit increases with the extraction rate or extractive capacity is fixed (Cairns and Lasserre 1986).

The grade selection problem is more

complicated when the resource price is stochastic. In particular, if a firm expects the price path to have random fluctuations around a trend, then the optimal response to a price increase can be to decrease extraction at a higher quality (lower cost) deposit and increase extraction at a lower quality (higher cost) deposit so that the average quality of extraction can decline in response to a price increase (Slade 1988).⁸ This provides some explanation for the stylized fact that average grade and the present value resource price are positively correlated in the long-run but average grade decreases in response to an increase in nominal price in the short-run.

A backstop technology that provides a substitute for a nonrenewable resource at a higher cost can be viewed as a higher cost deposit whose cumulative use is not limited, although there may be a finite limit to the availability of the substitute at any particular time. Substitution of solar energy for fossil fuels is the most commonly cited example of a backstop technology. In the absence of stock effects, the in situ value of the nonrenewable resource increases at the rate of interest until the nonrenewable deposit is exhausted just as the resource price reaches the marginal cost at which the backstop technology is available. With a stock effect, the in situ value for the nonrenewable resource can decline over time (Heal 1976) and may even be nonmonotonic (Farzin 1992), although the time path for user cost cannot be decreasing if the net benefit function is strictly concave in the resource stock and the rate of extraction (Livernois and Patrick Martin 1997). The arrival of new information about the cost or timing of availability of a backstop

⁸ The hypothesis that the trend in the resource price is zero is not rejected by price data for seven minerals from the period 1906-73 (Slade 1988).

technology can revise expectations about the future resource price path, and this can cause the observed time path for user cost to differ from the once-anticipated price path (Swierzbinski and Mendelsohn 1989b).

The grade selection problem becomes even more complicated when ore quality varies within a deposit and technological infeasibility or high cost prevents returning to extract any ore previously left behind as waste rock. A simple representation is where ore quality is greatest at the center of the deposit, declines symmetrically with distance from the center, and the grade distribution is the same through the length of the deposit. This physical representation lends itself to a model of cylindrical extraction where, at each point in time, the decision maker chooses the cut-off grade—the lowest ore quality extracted—as the radius of the cylinder, and the rate of depletion of the deposit as the length of the cylinder. The decision maker now has two control variables; metal production and extraction cost are functions of both the cutoff grade and the rate of depletion. There are two static efficiency conditions: (i) the cut-off grade is chosen so that the marginal return to lowering the grade is equal to the marginal cost of increasing the radius of the extracted cylinder; and (ii) the rate of depletion is chosen so that the marginal benefit of depletion is equal to the marginal cost of increasing the length of the extracted cylinder, including the user cost associated with the finite vein length. Because there are two dimensions to the extraction decision, there isn't a single marginal extraction cost, but rather a marginal cost in each of two dimensions. Consequently, it doesn't necessarily make sense to describe the in situ value of the resource stock as price less marginal cost. With a stationary demand curve

and no stock effects, the resource price rises at less than the rate of discount, in situ value increases at the rate of interest and the cutoff grade is decreasing over time. As in the standard case, a stock effect implies in situ value increases at less than the rate of interest (Cairns 1986). Since the deposit length can be exhausted without extracting all of the resource, there can be an exponentially increasing component to user cost even if the resource is not exhausted. If the rise in cost is such that the length of the deposit is not exhausted, then output and price are constant, the depletion rate decreases, and the cutoff grade increases over time. When combined with a model of exploration, the resource price can be increasing or decreasing over a particular time interval, although it eventually rises to the choke price (Cairns and Quyen 1998).

The optimal response of a competitive firm to a price change depends upon whether or not the price change was anticipated. The optimal cutoff grade is directly related to anticipated changes in the present value of the resource price. This tilts the depletion path of the scarce resource, the length of the deposit, toward the times when the present value price is greatest. The optimal response to an unanticipated price change depends upon how the slope of the new price path, as well as its level, differs from the original price path. When the life of the mine is endogenous and the expected price level changes but its time derivative remains the same, the optimal cutoff grade decreases (increases) when the price increases (decreases) (Jeffrey Krautkraemer 1989). This change in cutoff grade is consistent with a mining rule-of-thumb and offers another explanation for the empirical observation that average grade declines in response to

nominal price increases in the short run. When extractive capacity is constrained, the grade decrease means less metal is extracted in response to a price increase. This is consistent with the negative supply elasticity for South African gold mines (James Marsh 1983) and the observation that silver production declined in 1979 because higher prices made it economical to extract lower grade ore (H. J. Drake 1980). An analysis of the relationship between grade changes and price changes using South African and U.S. mining data suggests that grade changes are better described as responses to unanticipated price changes (Scott Farrow and Krautkraemer 1989).

3.4 *Market Imperfections and Other Factors*

In theory, a perfectly competitive market can allocate a nonrenewable resource efficiently over time as long as there is a complete set of markets, including forward, capital, and risk markets (Partha Dasgupta and Heal 1979). In the absence of forward markets, agents in the economy must form expectations about future prices. It is possible that the market could be following a short-run equilibrium price path in which both the static and dynamic efficiency conditions were satisfied but the transversality condition was not satisfied. That is, the user cost of the resource could be rising at the rate of discount so that expectations about future prices would be met, but in the absence of forward markets, the initial price level could be either too high or too low. If it is too low, then extraction is too great along the short-run equilibrium price path. At some point, either the price level must be corrected or the resource stock is exhausted too early. If it is too high, then extraction is too little along the short-run equilibrium

price path and cumulative extraction over the entire time horizon is inefficiently low.

In addition to the problems that are created by the absence of a complete set of forward markets, nonrenewable resource markets are subject to the same categories of market failures faced by other markets. The intertemporal nature of these markets can complicate the implications of the various market failures. In particular, whether a market imperfection results in a depletion rate that is greater than or less than an efficient depletion rate depends upon the intertemporal profile of the market imperfection—in particular, on the rate of change in the market imperfection compared to the discount rate (Sweeney 1978). These factors will not be examined in detail but some indication of their impact on the Hotelling implications is briefly discussed.

For example, market power is an essential feature of the petroleum market.⁹ A mining firm with market power faces a downward sloping demand curve, and profit maximizing extraction occurs where marginal revenue, rather than price, equals marginal extraction cost plus user cost. In the absence of stock effects, the difference between marginal revenue and marginal extraction cost increases at the rate of interest. The effect of market power on the intertemporal pattern of extraction depends upon how demand elasticity varies with the quantity produced. In the case of constant demand elasticity and zero marginal extraction cost, the intertemporal extraction pattern and

⁹ One indicator of the role of market power in the case of petroleum is the large divergence between the marginal cost of investment in capacity across countries, which varies from \$343 in Saudi Arabia to over \$10,000 in the United States (Adelman 1993). Marginal investment cost would be approximately the same across countries in a competitive market.

price path are the same under monopoly as under perfect competition (Joseph Stiglitz 1976). This is because lower current extraction allows greater future extraction and there is no advantage to altering the extraction pattern when demand elasticity is constant.¹⁰ More typically, demand elasticity increases with price, and the monopolist's extraction pattern is more conservative than what would occur under perfect competition: the price path begins higher and increases less rapidly under monopoly than under perfect competition. The effect of market power in an oligopoly or cartel setting further complicates the analysis of nonrenewable resource markets.¹¹

A wide variety of environmental externalities is associated with the extraction and consumption of nonrenewable resources (Charles Kolstad and Krautkraemer 1993). The impact of externalities on the market's depletion path can depend upon the exact nature of the externality. Two broad categories of externalities can be identified: flow externalities where the environmental damage is a function of the flow of emissions, such as photochemical smog from automobile exhaust; and stock externalities where the environmental damage is a function of cumulative emissions, such as the effect of atmospheric accumulation of carbon dioxide on global climate. Flow externalities can result in too rapid or too slow of a depletion rate, depending upon how the marginal external damage changes over

time, although if extraction is declining over time, then the marginal external damage is declining over time and the depletion path is tilted too much towards the present (Sweeney theorem). A stock externality would have the impact of a stock effect, and stock effects usually slow the rate of depletion (i.e., tilt it toward the future). Consequently, a stock externality would result in too rapid depletion and possibly too much cumulative extraction. Thus, one would expect that environmental externalities associated with nonrenewable resource use would result in too rapid a depletion of those resources.

The future values of a variety of important variables—future price, future extraction cost, the remaining resource stock, the outcome of exploration and development activities, and the cost and timing of the availability of a backstop technology—are uncertain. Uncertainty affects the intertemporal extraction pattern and price path in a variety of ways. For example, demand uncertainty can shift extraction from the future to the present if the degree of uncertainty increases with time, but can have the opposite effect if the variation in expected return increases with the quantity extracted. Moreover, the arrival of new information can cause a revision in future expectations that completely alters the extraction and price paths. Finally, the risk associated with holding a mineral asset can be diversified in a portfolio with other assets. Consequently, the return to holding the mineral asset—the rate of increase in in situ value—must be greater (less) than a risk free return when it is positively (negatively) correlated with the return to the portfolio (Gaudet and Ali Khadr 1991). Thus, the rate of change in in situ value could be greater than or less than the interest rate depending upon its covariance with the rate of return to other risky assets.

¹⁰ The exogeneity of the initial resource stock also is a critical assumption. If the size of the known stock is endogenously determined, for example through exploration, then the monopolist will produce less and sell at a higher price (Gérard Gaudet and Lasserre 1988).

¹¹ See Lasserre (1991) for an overview of duopoly and oligopoly in resource markets and David Teece, David Sunding, and Elaine Mosakowski (1993) for a review of nonrenewable resource cartels.

Finally, government interventions also can tilt the market's depletion path toward the present or the future. Nonrenewable resource industries are subject to a variety of taxes in addition to the taxes paid by all firms. One motivation for nonrenewable resource taxation is that nonrenewable resources are part of the national heritage and resource rents should accrue to the general welfare. Nonrenewable resources can be subject to severance taxes per unit extracted or royalty payments as a percentage of the resource price. In general, the effect of such a tax on the intertemporal extraction pattern depends upon how the present value of the tax changes over time—another case of the Sweeney intertemporal bias theorem. For example, the present value of a constant severance tax decreases over time and so shifts extraction from the present to the future. The impact of taxation also becomes more complex as additional features are added; e.g., with a stock effect, taxes can affect the total recovery of a mineral (Terry Heaps 1985). Since extraction taxes affect the expected value of new reserves, they also will impact exploration and development activities and investment in capacity, both of which can distort the extraction path.

4. *Empirical Analyses*

Data availability has been a significant problem for efforts to empirically test the theoretical implications of the Hotelling model in a straightforward fashion. Perhaps the most basic theoretical implication concerns the dynamic behavior of in situ value, but market data for in situ values are not readily available. The extraction, milling, and refining processes are often vertically integrated and sales of proven reserves are infrequent. Market data

for the value of mining firms are available but such values include assets other than the nonrenewable resource, and extraction cost data are usually proprietary information. Consequently, the empirical analysis of nonrenewable resource scarcity has taken a variety of less direct paths, including examination of the dynamic behavior of resource prices rather than in situ values, the reconstruction of in situ values through various means, and the examination of the relationship between the average reserve value and current net price.

4.1 *Resource Prices*

The classic empirical study by Barnett and Morse (1963) found a level trend for an index of mineral prices relative to the price of non-extractive commodities over the period 1870 to 1957, with a good deal of short- and intermediate-term variation. The index fell from the 1870s to the 1890s, then rose until World War I, and then fell again until the 1930s. This variation is attributed to "short-term relative inflexibility of minerals output to changes in demand from movements in the economy as a whole." An extension of the data to 1973 found a positive but statistically insignificant time trend coefficient but the pattern of price movements is unstable, making it difficult to draw any general conclusion concerning the trend (V. Kerry Smith 1978).

Constant or falling nonrenewable resource prices are inconsistent with the basic Hotelling model with zero extraction cost. Of course, as discussed above, exploration and discovery, or technological change that lowers extraction cost, can generate a decreasing resource price even as in situ value is increasing. Eventually, the impact of increasing user cost outweighs the decrease in extraction cost, or exploration opportunities

are exhausted, so that price begins to increase and the price path is U-shaped. Empirical support for the U-shaped price path hypothesis is provided by estimates of linear and quadratic trends for the price paths of eleven minerals and an aggregate minerals price index with data from 1870–1978 (Slade 1982b). Four of the eleven minerals and the aggregate index have a negative linear trend but only 7 of the 12 linear trend coefficients are statistically significant at the 90 percent level. For a quadratic price path, the linear coefficients for all 12 estimated equations are negative (10 are statistically significant at the 90 percent level) and the coefficients of all 12 quadratic terms are positive (11 are statistically significant at the 90 percent level). In each case, the minimum point of the fitted price path occurs before the end of the data series indicating that nonrenewable resource prices would be trending upward from 1978. Extending the data to 1988 and the use of an error-correction framework to separate short-run deviations from the long-run relationship between resource prices and the deflator results in essentially the same outcome (B. Moazzami and F. J. Anderson 1994). Darwin Hall and Jane Hall (1984) also find some evidence of increasing nonrenewable resource prices in the 1970s, although the evidence for increasing nonfuel mineral prices is weak.

However, nonrenewable resource prices did not continue to trend upward after the 1970s, as can be seen in Figures 1–11. This change in trend is consistent with the observation that there isn't a stable linear trend to most resource price time series (V. Kerry Smith 1978). As it turns out, the estimated coefficients of the quadratic trend also change with the period of estimation—that is, no single quadratic equation ex-

plains the entire sample period (Peter Berck and Michael Roberts 1996). In addition, the empirical evidence is that the natural resource prices are difference stationary rather than trend stationary, as implicitly assumed in Slade (1982b), and the prices predicted for the year 2000 by difference stationary models are much lower than the prices forecast by a trend stationary model (Berck and Roberts 1996).

4.2 *In Situ Values*

The dynamic behavior of in situ value would provide a more direct test of the Hotelling rule. Under the assumption that a mining firm satisfies the static efficiency condition, a time series for in situ value can be constructed as the difference between price and marginal cost from an estimated cost function and a time series for the expected resource price path (Farrow 1985), or through the use of the dual relationship between the in situ value and the marginal value of the extracted resource as derived from a restricted cost function for the final output (Robert Halvorsen and Tim Smith 1991). Given a time series for user cost, a discrete-time version of the dynamic efficiency condition can be estimated by regressing user cost in period t , λ_t , on user cost from the previous period, λ_{t-1} , and the marginal stock effect, C_s . Dynamic efficiency requires $\lambda_t = (1 + \delta)\lambda_{t-1} + C_s$, so the coefficient on the lagged user cost should be one plus the firm's discount rate and the coefficient on the stock effect should be one. Empirical tests of the dynamic behavior of in situ value have generally failed to support the Hotelling implication that in situ value increases at the rate of interest. An exception is the case of nickel for the time period 1946–49, 1956–73 (Stollery 1983). The International Nickel Company of Canada is the dominant firm in

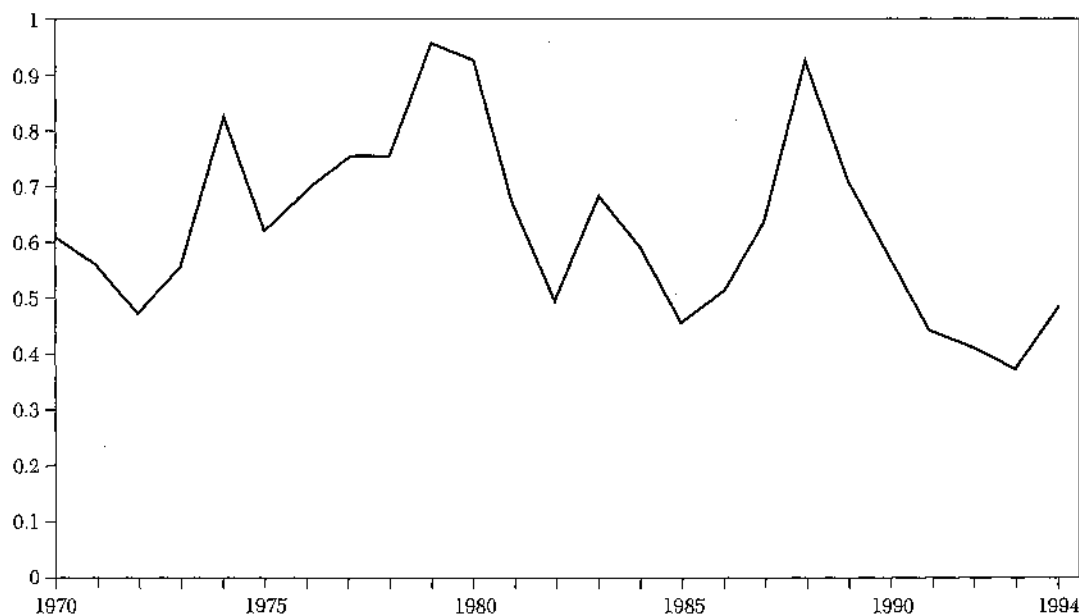


Figure 1. Real Price of Aluminum, 1970-94 (\$/pound)

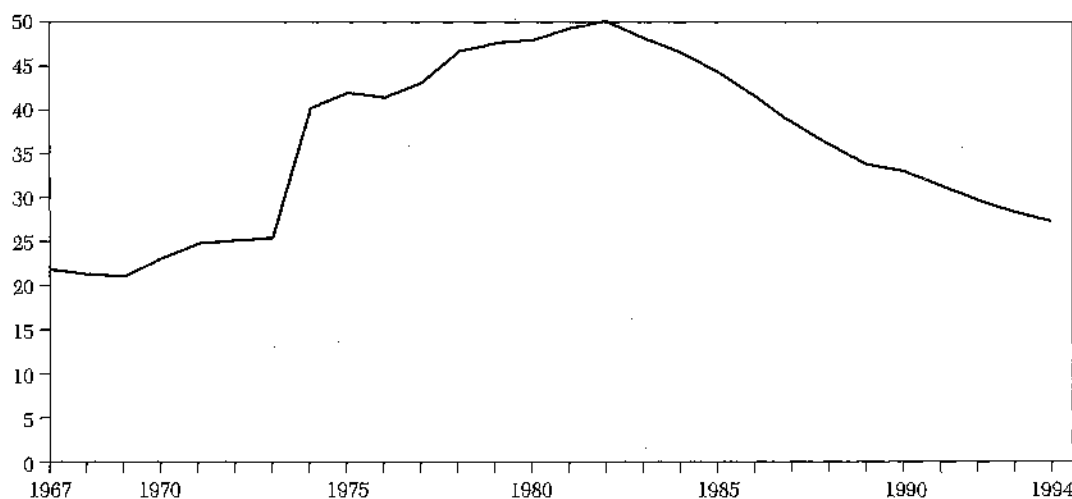


Figure 2. Real Price of Coal, 1967-94 (\$/ton)

nickel supply and is taken as a price leader.¹² The dynamic behavior of *in situ* value is consistent with present value maximization but it also is consis-

tent with a mark-up pricing model (Cairns 1985).

Less successful attempts to verify the Hotelling implication for dynamic behavior of *in situ* value include those by Farrow (1985) and Halvorsen and Tim Smith (1991). Using monthly proprietary production and cost data from a

¹² Since this firm is not a perfect competitor, a demand curve was estimated in order to generate a time series for marginal revenue.

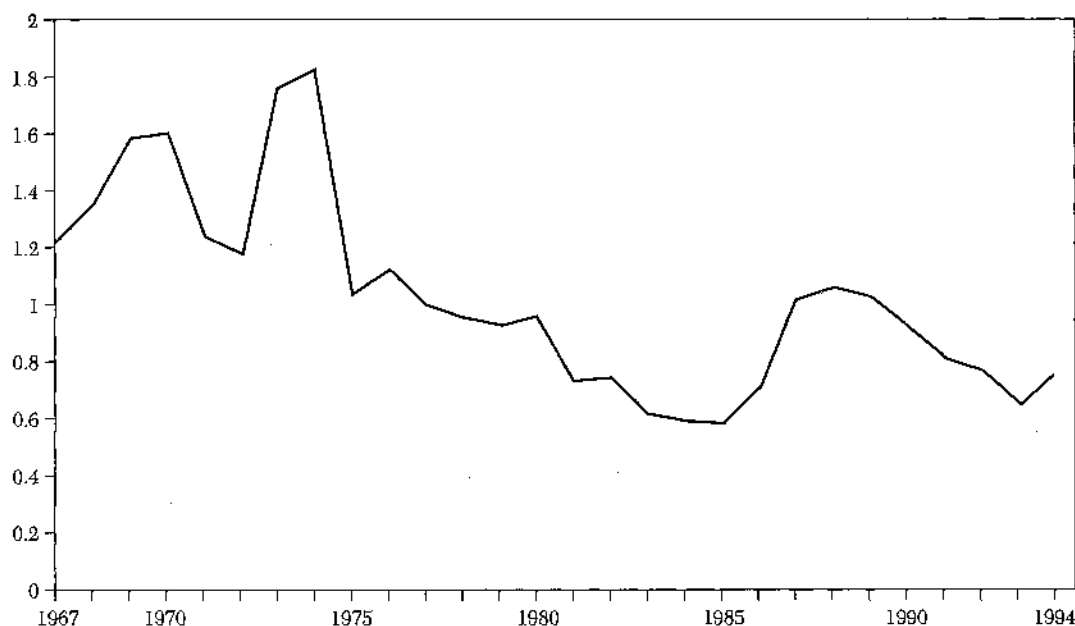


Figure 3. Real Price of Copper, 1967-94 (\$/pound)

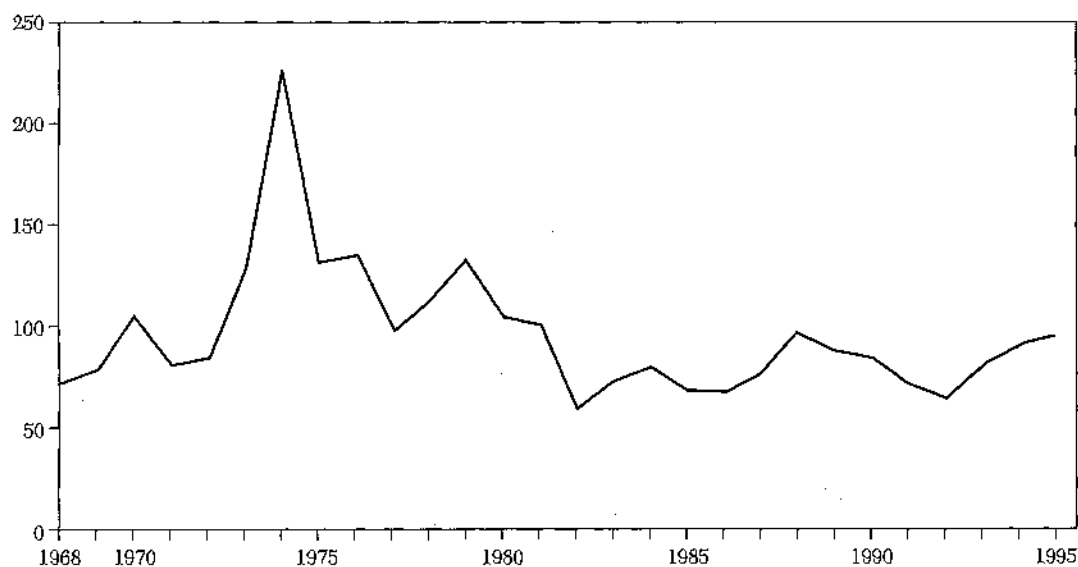


Figure 4. Real Price of Iron, 1968-95 (¢/lb, Pittsburgh price)

single mining firm, negative values, sometimes statistically significant, are obtained for the coefficients of both the discount rate and the stock effect variable (Farrow 1985). This result is

consistent across a variety of econometric specifications, including those that incorporate a time-varying discount rate, different price expectation formulations, and a capital constraint on

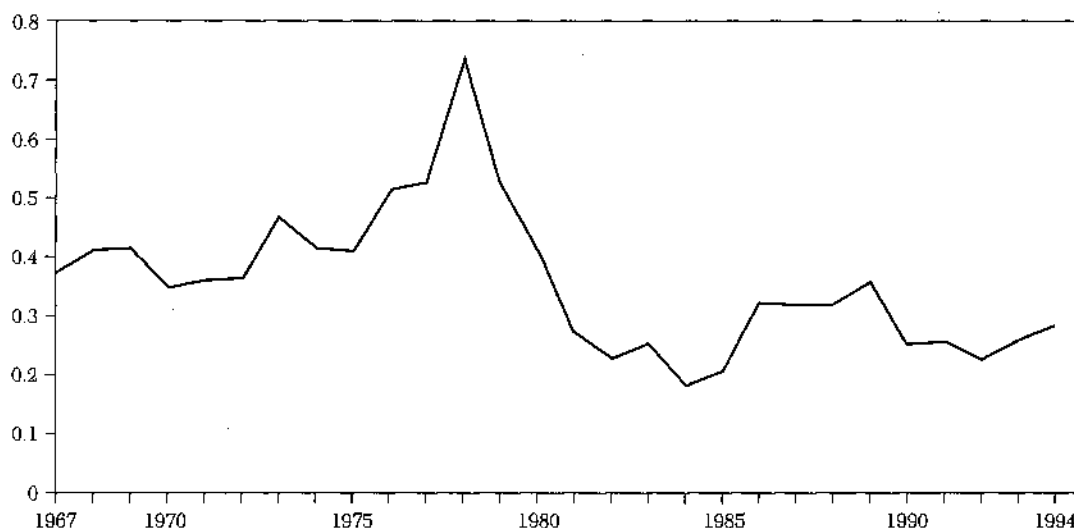


Figure 5. Real Price of Lead, 1968-95 (\$/pound)

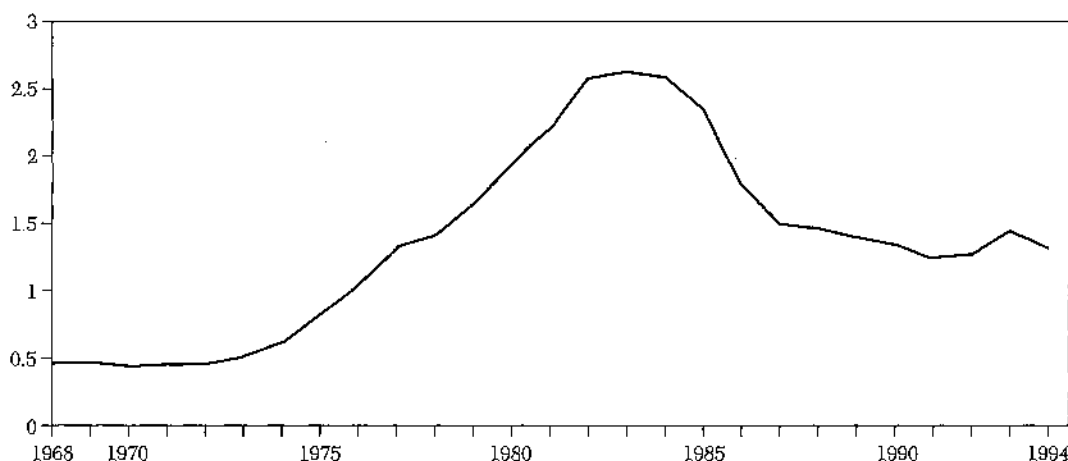


Figure 6. Real Price of Natural Gas, 1968-94 (\$/1000 cu.ft.)

output. In a study using aggregate production and cost data for the Canadian mining industry, the parametric restrictions implied by the dynamic efficiency condition are rejected at the 1 percent level with both constant discount rates and variable discount rates (Halvorsen and Tim Smith 1991).¹³ An

¹³ The movement of the aggregate user cost can be affected by changes in the mix of outputs of different minerals so Halvorsen and Smith suggest their results should be considered tentative.

alternative to constructing a time series for user cost is to estimate the parameters of the dynamic efficiency condition directly along with the cost function using the Generalized Method of Moments (Denise Young 1992). An annual panel data set for 14 small Canadian mines provide a poor fit for the dynamic optimization equation.

Given the many maintained hypotheses implicit in these tests of the Hotelling rule, and the variety of



Figure 7. Real Price of Nickel, 1968-95 (\$/pound, London Metal Exchange)

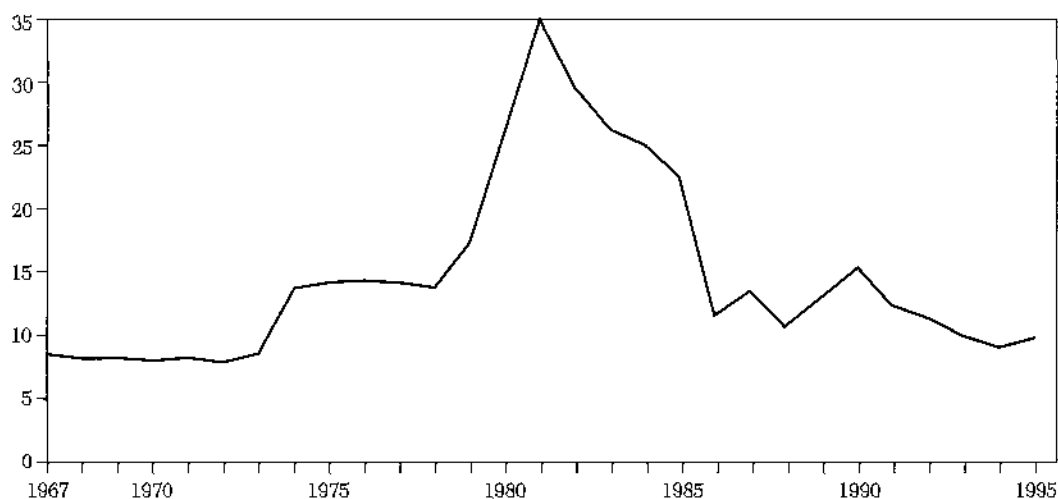


Figure 8. Real Price of Petroleum, 1967-95 (\$/bbl)

factors that can complicate optimal extraction paths, it is perhaps not too surprising that the basic Hotelling model does not provide an adequate explanation of the data. Halvorsen and Tim Smith (1991) suggest that the assumptions of complete certainty and perfect arbitrage may need to be relaxed in order to give an adequate description of nonrenewable resource extraction.

They also note that the tested model does not incorporate the possibility of a variety of uncertain events such as invention of substitutes or new discoveries that could cause shifts in the time path for in situ value. Farrow (1995) points to the mining rule-of-thumb that the cutoff grade should decrease in response to a resource price increase as a possible explanation for the failure of

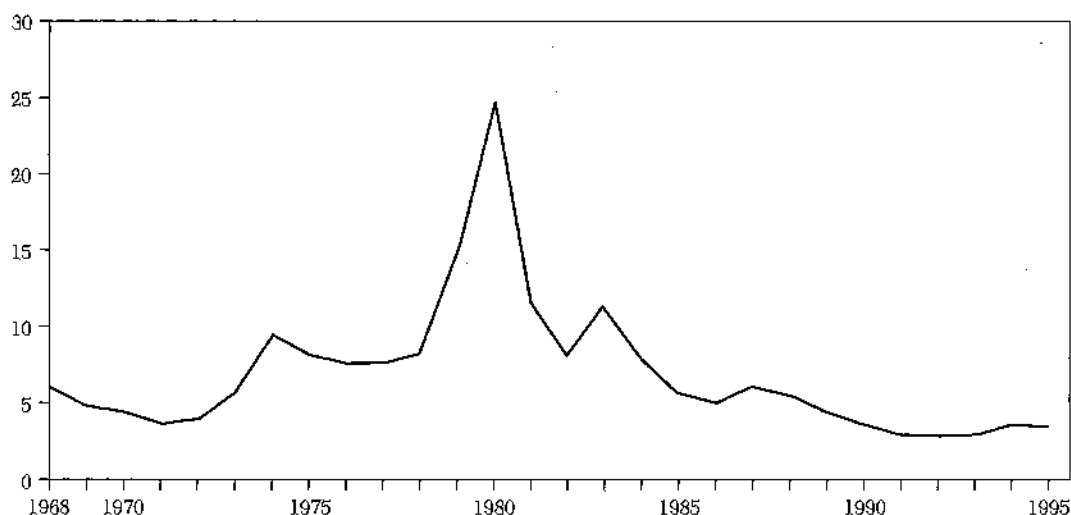


Figure 9. Real Price of Silver, 1968-95 (\$/troy ounce)

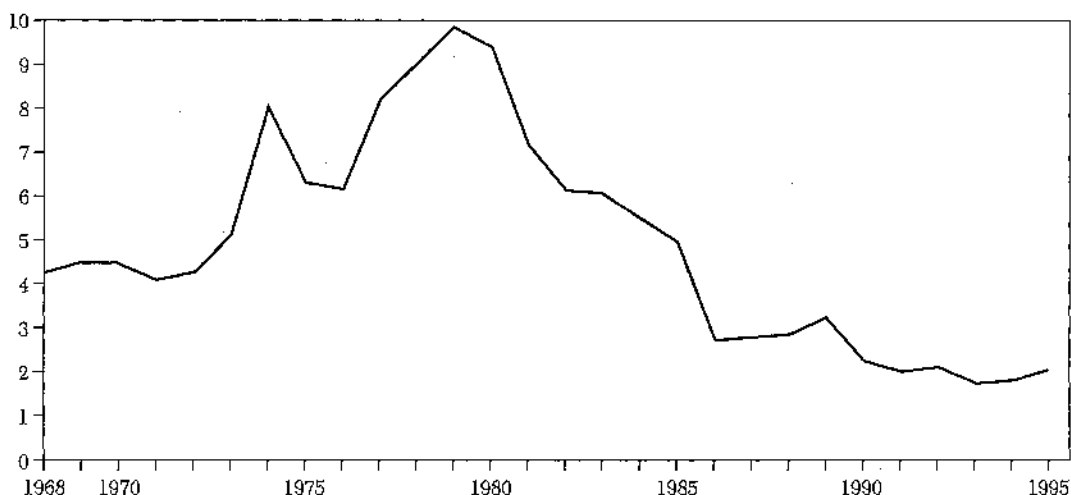


Figure 10. Real Price of Tin, 1968-95 (\$/pound)

the model to explain the data. As seen in the previous section, this can be a present value maximizing response to an unanticipated increase in the resource price path. Such a response is more consistent with mining data from South Africa and the United States than is the basic Hotelling model (Farrow and Krautkraemer 1989). The cutoff grade model also is consistent with Canadian gold mining data (Cairns 1990).

4.3 Hotelling Valuation Principle

An alternative method for testing the Hotelling model examines the relationship between average reserve value and current net price using cross section data (Merton Miller and Charles Upton 1985a). When extraction cost is proportional to the extraction rate and there are no stock effects, the present value of the resource price less marginal



Figure 11. Real Price of Zinc, 1968-95 (¢/pound)

extraction cost is the same in any period with positive extraction.¹⁴ In a discrete time formulation, we have:

$$P_0 - C_0 = \frac{P_t - C_t}{(1+r)^t} = \lambda, \quad (10)$$

where P_t and C_t denote price and marginal extraction cost at time t ; r denotes the interest rate; and λ denotes in situ value. Then the value of reserves can be written in terms of the initial resource price and initial extraction cost:

$$V_0 = \sum_{t=0}^T \frac{P_t - C_t}{(1+r)^t} q_t = \lambda \sum_{t=0}^T q_t = \lambda S_0 = (P_0 - C_0) S_0 \quad (11)$$

where V_0 denotes reserve value, q_t denotes extraction at time t , and S_0 is the initial resource endowment. Dividing by the initial endowment gives:

¹⁴ The assumption of constant returns to scale is fairly restrictive in that it requires the price path, $P(t)$, to satisfy $P/P + (1 - \lambda/P)r$, where γ is the constant marginal extraction cost and r is the discount rate, in order to get positive extraction at each point in time.

$$\frac{V_0}{S_0} = (P_0 - C_0), \quad (12)$$

a simple rule, known as the Hotelling Valuation Principle, that average reserve value equals current net price, and so it is independent of future prices and extraction costs.¹⁵

With stock effects, or if average extraction cost increases with the rate of extraction, the relationship between average reserve value and current net price includes a constant term:

$$\frac{V_0}{S_0} = \alpha + (P_0 - C_0), \quad (13)$$

where the constant α can be positive or negative. Miller and Upton (1985a) argue that this constant term is independent of $P_0 - C_0$ and any future net prices. However, the constant term does contain q_0 and q_t , both of which are functions of the future net price relative to the current net price. The Hotelling Valuation

¹⁵ In addition, the assumption of constant returns to scale and positive extraction places restrictions on the price path—see footnote 14 above.

Principle will overvalue the resource endowment when the expected rate of increase in net price is less than the interest rate (Adelman 1993).

The results of empirical tests of the Hotelling valuation equation are mixed. The model was found to be consistent with pooled, cross-section data from December 1979 to August 1981 for 39 oil- and gas-producing firms in the United States (Miller and Upton 1985a). The value of reserves is calculated from the market value of the firm with adjustments for claims by creditors and non-reserve assets. The estimated coefficient for the current net price is 0.91 and the estimate is not significantly different from one. A subsequent test of the Hotelling Valuation principle using data from August 1981 to December 1983 produced a quite different result: the estimated coefficient for current net price dropped to 0.466 and was significantly different than one (Miller and Upton 1985b). There is additional empirical evidence that the per unit value of reserves for oil and natural gas is only about one-half of current net price (G. C. Watkins 1992, Adelman 1993).

An explanation for why the Hotelling Valuation Principle might overvalue reserves, at least in the case of oil and natural gas production, is that it affords producers greater flexibility for choosing output than they actually have. The extraction of petroleum over time is restricted by declining well pressure as the reservoir is depleted. If the rate of extraction declines at the rate a because of declining well pressure, the average reserve value is

$$\frac{V_0}{S_0} = \frac{a}{a + r - g} (P_0 - C_0), \quad (14)$$

where g is the expected rate of change in net price (Adelman 1993). The result $V/S = 0.5(P_0 - C_0)$ is obtained when the

expected rate of increase in net price is zero and the rate of decline in well pressure is approximately equal to the interest rate, which is consistent with a relatively constant net price and a rate of decline in oil pressure and interest rate that are both about 10 percent (Adelman 1990).

4.4 Asset Arbitrage Models

Asset arbitrage implies that the rate of return to holding a nonrenewable resource asset, including any capital gain, should be related to the rate of return to other assets in the economy. Since the return to a nonrenewable resource stock is primarily any capital gain, the demand for holding a nonrenewable resource stock is a function of the expected rate of appreciation of the value of the resource stock relative to the return to other assets as represented by the rate of interest. The change in the value of the stock, of course, is a function of the rate of change in the resource price. A reduced form equation of a supply-demand model for the resource stock gives the rate of change in resource price as a function of various factors affecting supply or demand, including the growth rate of the economy, the market rate of interest, lagged resource prices, and changes in the interest rate (Heal and Michael Barrow 1980).

While this type of model does a good job of explaining mineral price behavior (V. Kerry Smith 1981), a consistent empirical finding is that movements in the resource prices are related to changes in the interest rate rather than the level of the interest rate as the Hotelling model predicts (Heal and Barrow 1980, Terence Agbeyegbe 1989). There will be a relationship between changes in the interest rate and the rate of change in price if either supply or demand is a function of the interest rate. Since

there is reason to believe that the interest rate can affect the demand for the nonrenewable resource through its effect on economic activity and the supply of the resource through its effect on extraction cost, this relationship is not particularly surprising. A greater concern is the lack of an empirical relationship between the rate of price appreciation and the level of the interest rate, since this implies the resource price is constant when the interest rate is constant.

Of course, it is the resource price net of extraction cost that should increase at the rate of interest or at less than the rate of interest with stock effects. In addition, other factors such as new discoveries and tax policies will affect the movement of user cost and resource prices. Finally, the rate of change in in situ value could be greater than or less than the interest rate depending upon its covariance with the risk-free rate of return (Gaudet and Khadr 1991). A recent study used aggregate Canadian mineral data for the time period 1950–89 with in situ value calculated as price minus average extraction cost to test a risk-adjusted Hotelling model (Young and David Ryan 1996). While including risk improved the performance of the Hotelling model and the data did not reject the model, the adjustment for risk did not completely reconcile the Hotelling model with observed price movements. Slade and Henry Thille (1997) come to a similar conclusion using panel data for Canadian copper mines that allows a richer treatment of extraction cost, although they find that macroeconomic and financial variables (such as gross domestic product and exchange rate) have greater statistical significance than the extraction cost variables.

There is strong empirical evidence that the basic Hotelling model of finite

availability of nonrenewable resources does not adequately explain the observed behavior of nonrenewable resource prices and in situ values. This is not terribly surprising given the many other features of nonrenewable resource supply, such as exploration for and discovery of new deposits, technological change, and capital investment, that alter the implications of finite availability. It seems clear that these other factors have overshadowed finite availability of the resource as determinants of the observed dynamic behavior of nonrenewable resource prices and in situ values.

5. Resource Scarcity Indicators

Given the recurring concern about nonrenewable resource availability, it seems desirable to have a reliable indicator of how nonrenewable resource scarcity is changing over time. Indicators of resource scarcity can be physical or economic. In the strictest sense, the conservation of mass suggests that the physical availability of matter doesn't change with production or consumption. Consequently, it is the structural form of the matter and its availability for different uses that really matters. At least in some sense then, even the common physical measures of resource availability have some economic content. In addition, physical availability by itself is not a sufficient indicator of economic scarcity. The crustal abundance of a mineral, a common measure of the ultimate availability of a mineral, is certainly greater than ultimate cumulative extraction of the mineral. Technological changes affect both the demand for and the supply of a particular resource, and therefore its relative scarcity, in a variety of anticipated and unanticipated ways.

The classification scheme of the United States Geological Survey defines

TABLE 1
RESERVE TO CONSUMPTION RATIOS, 1994

Mineral	Reserve Life Index	Reserve Base Life Index
Aluminum	207	252
Copper	33	62
Iron Ore	152	233
Lead	23	47
Nickel	59	137
Tin	41	59
Zinc	20	48

Source: World Resource Institute (1996).

total resources as materials that have been discovered or might be discovered and used (Donald Brobst 1979). Reserves are that portion of total resources that can be economically extracted. Undiscovered resources are classified as hypothetical, if in a known mining district, or speculative. Identified but currently noneconomic resources are categorized as paramarginal or submarginal. The physical measures of reserves often are compared to measures of the rate of use in order to determine the remaining life of the reserves. Estimates for the remaining life of reserves for several minerals are given in Table 1. Here, the term reserves includes deposits that are currently economically recoverable, and the reserve base includes recoverable reserves and resources that are marginally economic and some resources that currently are not economically recoverable. Since reserves are defined in terms of economic recovery, whether or not a deposit is a reserve changes with the resource price and extraction cost. In addition, since costly investment is required to "prove" reserves, there is limited incentive to prove reserves beyond a certain point. The reserve to consumption ratio for petroleum for

TABLE 2
PETROLEUM RESERVES TO CONSUMPTION

Year	Ratio (years)
1950	22
1960	37
1972	35
1980	27
1990	45

Source: Slade (1987); World Resource Institute (1996).

various years is presented in Table 2. This ratio increased from 35 in 1972 (Slade 1987) to 45 in 1990 (World Resource Institute 1994) even though commercial energy consumption increased by more than 50 percent between 1971 and 1991 (World Resource Institute 1994). Physical measures of reserves probably have more meaning as an inventory than as a measure of scarcity (Adelman 1993).

Three economic variables have been used as economic indicators of resource scarcity: extraction cost, price and user cost. These three measures are related to each other through the static efficiency condition: $P = \lambda + C_q$. There has been much debate about which measure is the best scarcity indicator or even whether or not economic indicators can measure scarcity.¹⁶ One view is that a scarcity indicator "... should summarize the

¹⁶ Richard Norgaard (1990) argues the Hotelling framework can be characterized by the following syllogism: If resources are scarce and if resource allocators are informed of resource scarcity, then economic indicators will reflect this scarcity. He asserts that empirical analyses of scarcity have ignored the second "if" in the syllogism and concludes that economic indicators of scarcity are logically flawed. An alternative interpretation is that economic indicators of scarcity reflect available information about scarcity at a particular time and that information changes over time. As Adelman (1990) observes, "A market in mineral reserve values is a market in good and bad ideas about future scarcity."

sacrifices, direct and indirect, made to obtain a unit of the resource" (Anthony Fisher 1979). This suggests the use of price, since it would incorporate both the current extraction cost and the user cost that captures the Hotelling and Ricardian stock rents. An alternative requirement "... is that the index go up when underlying determinants shift to increase actual or expected demand for the resource relative to the expected supply" (Gardner Brown and Barry Field 1979). A difficulty is that each of these economic indicators can fail to indicate decreasing resource availability under different circumstances.

The different scarcity indicators can move in opposite directions under some circumstances. For example, as seen in Section 2, extraction cost can be decreasing even as user cost and price are increasing as the resource stock is exhausted.¹⁷ This stems from the inherent shortcoming of extraction cost as a static rather than a dynamic measure—it is not as forward looking as either price or user cost. In addition, extraction cost captures information about only the supply side of the market. Scarcity could be increasing as demand grew more rapidly than extraction cost decreased, or extraction cost could be increasing as scarcity decreased because of the development of substitutes for most uses of a particular resource.

Both price and user cost also can be misleading indicators of a resource scarcity trend. As demonstrated above, price can decrease as scarcity increases if the rate of decrease in extraction cost is great enough. While the decrease in extraction cost indicates that the resource is more readily available at that particular time, the availability of the resource in the future is decreasing

rather than increasing. The resource price will begin increasing at some time in the future, and the user cost would signal this increasing scarcity earlier than the resource price. The resource price also may reflect changes in market conditions other than increasing scarcity, such as the market power of OPEC, or the Hunt brothers attempt to corner the silver market in 1979–80. Both the resource price and extraction cost understate resource scarcity if the environmental costs of resource extraction and consumption are not captured by the market, and they will understate the degree to which scarcity is increasing if those environmental costs are increasing over time. In situ value can be decreasing when economic scarcity is increasing. If there is a backstop technology that provides a substitute for the nonrenewable resource at a cost low enough that the resource stock is not exhausted, then there is no Hotelling rent and in situ value can be decreasing over time even as the resource price is strictly increasing as the resource is depleted (Heal 1976). Because of the possible divergent movements of the economic measures of resource scarcity, it is useful to examine all three measures in order to get a sense of what is happening to nonrenewable resource scarcity over time.

Technological innovation has led to an overwhelming downward trend in extraction cost even as the quality of exploited deposits has declined. The earliest attempt to measure changes in resource scarcity focused primarily on the change in the ratio of a measure of inputs—either labor or a weighted average of labor plus capital input—to net extractive output over the period 1870–1958, and found a significant downward trend for this measure from 1890 forward (Barnett and Morse 1963). Moreover, the decline in unit cost for

¹⁷ This was the case for Douglas fir from 1940 to 1970 (Brown and Field 1979).

extractive output was greater than the decline in the same measure of unit cost for non-extractive output. An extension of the time period to 1970 found the rate of decrease in extraction cost continued at an increasing rate (Manuel Johnson, Frederick Bell, and James Bennett 1980). There is a statistically significant increase in extraction cost for U.S. coal and petroleum in the 1970s (Hall and Hall 1984), although this could be the response to higher prices that resulted from changes in the exercise of market power by OPEC rather than from changes in scarcity. The extraction cost for ferro alloys and nonferrous metals continued to decline in the 1970s, although the decline is not always statistically significant (Hall and Hall 1984).

As discussed in the previous section, the time trend for an index of mineral prices is roughly constant over the period 1870–1958, with short-term up and down movements. Mineral prices tended to be increasing in the 1960s and 1970s, which has been interpreted as the beginning of the upward sloping portion of a U-shaped price path (Slade 1982b; Hall and Hall 1984). But resource prices did not continue to follow an upward trend after 1980 and declined over much of the last 15 years. Figures 1–11 present more recent price data for the nonrenewable resources examined in Slade (1982b).¹⁸ Simple OLS regressions for the periods re-

ported in these figures show a negative time trend for eight of the eleven resources, although the negative coefficient is statistically significant only for copper, lead, and tin. Coal, natural gas, and petroleum prices have a positive time trend, although the estimated coefficient is statistically significant only for natural gas. The linear trend is a poor fit in most cases. This interval, of course, is too short to draw any strong conclusions regarding the time trend of nonrenewable resource scarcity. The silver market bubble and the second oil market crisis of the decade occurred in the late 1970s and probably affected other nonrenewable resource markets as well.

Empirical estimates of the movement of user cost over time also fail to find much evidence of increasing resource scarcity. The user cost for nickel increases slightly from 1950 to 1971, although user cost is a relatively small portion of the price of nickel (Stollery 1983). The user cost for an aggregate of Canadian minerals has a slightly positive, but statistically insignificant, trend over the period 1956–74 (Halvorsen and Tim Smith 1991). Decreasing trends in user cost also have been found for petroleum on the U.K. continental shelf, 1975–86 (M. Hashem Pesaran 1990), and Canadian asbestos (Lasserre and Pierre Ouellette 1991). Under certain conditions, marginal discovery cost can be used as a proxy for in situ value, and marginal discovery cost for Alberta oil and gas increased during 1970s (Perry Sadorsky 1991). However, the higher discovery cost also may reflect the market power of OPEC. In a competitive world, marginal development costs would be equal across locations, but marginal development cost in the Persian Gulf is much lower than in other parts of the world (Adelman 1990). Output from OPEC members is lower than

¹⁸ Iron price data are from Commodity Research Bureau (various years). Price data for coal, natural gas, and petroleum are from Annual Energy Review, 1995, Energy Information Agency, Department of Energy (<http://www.eia.doe.gov>). For the remaining resources, price data are U.S. prices from the United States Geological Survey, Minerals Information and Statistical Compendium (<http://minerals.er.usgs.gov>). All nominal prices are deflated by the U.S. Consumer Price Index, 1982–84 = 100, from 1996 Economic Report of the President (<http://www.access.gpo.gov/eop/index96.html>).

would occur under competition, and the higher price that results from restricted output encourages greater development at higher cost in other locations.

Economic indicators of nonrenewable resource scarcity do not provide evidence that nonrenewable resources are becoming significantly more scarce. Instead, they suggest that other factors of nonrenewable resource supply, particularly the discovery of new deposits, technological progress in extraction technology, and the development of resource substitutes, have mitigated the scarcity effect of depleting existing deposits. It is an open question as to whether or not these factors will continue to keep pace with depletion, particularly with growing population and economic development in much of the world.

6. Sustainability and Nonrenewable Resources

The term "sustainability" and the phrase sustainable development have become significant watchwords in the last decade. While there is an abundance of definitions of sustainability, it basically gets at the issue of whether or not future generations will be at least as well off as the present generations. Although the availability of nonrenewable resources is only one of the many dimensions of sustainability, it is the focus of discussion here. The measures of resource scarcity discussed in the previous section do not address the impact of increasing natural resource scarcity on the growth of an economy. While greater availability of nonrenewable resources enhances the opportunities for production and consumption, it can be possible for an economy to sustain itself even as the scarcity of a particular nonrenewable resource increases. In this section, the issues

surrounding the effect of nonrenewable resource depletion on an economy's ability to maintain its level of well-being are addressed from a neoclassical perspective, with attention given to some critiques of that approach. Since national income accounts are often used as a measure of economic well-being, the section also examines the incorporation of nonrenewable resource depletion in the national income accounts.

6.1 *Nonrenewable Resources and Economic Growth: A Neoclassical Approach*

In the context of a neoclassical growth model with a composite consumption good, the most fundamental requirement for the feasibility of sustained economic well-being, when production is dependent upon a finitely available nonrenewable resource, is that the average productivity of the resource is unbounded as the resource input goes to zero.¹⁹ If the average product of the resource is bounded above, then there is a finite limit to cumulative production and no positive level of production and consumption can be sustained indefinitely. The average product of the resource, of course, is a function of the technology and the availability of other inputs. Technological progress and capital-resource substitution, then, are two means of increasing the productivity of the nonrenewable resource. In particular, an economy can sustain a positive level of consumption and can even grow over time if the ratio of the rate of resource-augmenting technological progress to the rate of population growth is at least as great as the output share of

¹⁹ Neoclassical growth models are a useful tool for gaining insights into the key factors that determine the ability of an economy to sustain itself and are not intended to be taken as literal descriptions of the economy.

the resource (Stiglitz 1974).²⁰ Capital-resource substitution allows a non-decreasing consumption path if the elasticity of substitution between reproducible capital and the nonrenewable resource is greater than one or if the elasticity of substitution equals one and capital's output share is greater than the resource's output share (Dasgupta and Heal 1974).

The optimality of sustained growth depends upon whether or not the economy is patient enough to allow technological progress or capital accumulation to overcome the drag of nonrenewable resource depletion. In a present value utilitarian framework, the economy's patience is captured by the social rate of time preference. With technological progress, the growth rate in per capita consumption is positive if the ratio of the rate of technological progress to the output elasticity of the resource is greater than the rate of discount (Stiglitz 1974). In the case of capital-resource substitution, the economy must be willing to continue to accumulate capital to offset resource depletion, and this is the case as long as the lower bound of the marginal productivity of capital is greater than the rate of time preference. Otherwise, current consumption eventually provides greater present value utility than the future output of additional capital and capital accumulation stops. Since sustained growth depends upon the substitution of capital for the resource, eventually production and consumption must fall

to zero. In the case of the Cobb-Douglas production function, the limiting value of the marginal productivity of capital is zero, so the social rate of time preference must be zero in order for the economy to find it optimal to sustain a positive consumption level.

With a nonrenewable resource, then, the social rate of time preference can affect the economy's asymptotic growth rate and not just the asymptotic level of well-being. In the standard neoclassical growth model, future consumption is greater than current consumption as long as the initial capital stock is less than the steady-state capital stock. In the case of production with a nonrenewable resource, it seems more likely that future consumption can be less than current consumption, and so the issue of equitable intertemporal resource allocation is perhaps even more important. A Rawlsian-type intertemporal criterion that seeks to maximize the level of consumption that can be maintained perpetually provides an alternative to present value maximization as a social welfare criterion.²¹ This criterion is not particularly satisfying if the initial capital stock is small, since it would not allow additional capital accumulation in order to make the future better off at the expense of the current generation. With an essential nonrenewable resource, capital accumulation must occur as an offset to resource depletion if a constant consumption path is to be followed. In the case of a Cobb-Douglas production function with no population growth and no technological progress, such a path is feasible if the output share for capital is greater than the output share for the resource (Robert Solow 1974).

An interesting feature of the constant

²⁰ This is with a Cobb-Douglas aggregate production function with constant returns to scale. More generally, non-decreasing per capita consumption is possible if and only if $\tau > (\alpha + \beta - 1)n$, where τ is the rate of technological progress, n is the population growth rate, α and β are the output elasticities with respect to capital and labor respectively. That is, the sum of the gains from technological progress and returns to scale must be large enough to offset the increased demand for the resource due to the growing population.

²¹ In essence, the social rate of time preference is zero and the elasticity of the marginal utility of consumption is infinite.

consumption path is that it requires investing the rents from nonrenewable resource extraction into capital accumulation at each point in time (John Hartwick 1977).²² In essence, the value of the economy's assets remains constant over time and the economy consumes the interest on those assets (Solow 1986).²³ The "Hartwick rule" that constant consumption requires zero net investment also applies in a more general setting of an economy with many capital goods and natural resource assets that can generate a variety of commodities and amenities (Avinash Dixit, Peter Hammond, and Michael Hoel 1980). The zero net investment rule must be followed at each point in time; it is possible for the economy to have zero or positive net investment at a given point in time and not be able to sustain the current level of consumption if the capital and resource prices are not those implied by the constant consumption path (Geir Asheim 1994). In addition, the zero net investment rule would include all natural resource assets, of which many very important ones—biological diversity, climate stability, etc.—are not market commodities and are not included in the standard national income accounts.

Sustaining the economy with capital-resource substitution and/or technological progress requires the average productivity of the nonrenewable resource to be unbounded. This implies that the sustained level of consumption can be achieved with vanishingly small levels of the resource input, and this certainly will ultimately run counter to physical laws of nature. A given amount of mate-

rial output requires a minimum amount of material input, and unless material output goes to zero as the economy grows, some positive level of resource input must be maintained. This implies the average productivity of the resource is bounded above and only a finite output can be produced from a finite resource stock.²⁴ This essentially requires that sustainability ultimately must rely upon substitutes for the nonrenewable resource derived from renewable resources or backstop technologies. In both cases, there is an upper bound on the long-term flow of the substitute input per period of time and the economy tends to move to a steady-state determined by the social rate of time preference and either the marginal regeneration rate of the renewable resource or the marginal cost at which the backstop becomes available. It is possible that the social rate of time preference can be high enough that a renewable resource is exhausted or the backstop is never used.

Given the many factors that can mitigate nonrenewable resource scarcity—the availability of substitutes, the discovery of new deposits, capital-resource substitution, technological advances in resource extraction and commodity production—the finite availability of nonrenewable resources for commodity production may not be as pressing a problem as the environmental impacts of nonrenewable resource use.²⁵ For example, it may be desirable to stop combustion of fossil fuels because of the environmental cost of atmospheric carbon accumulation before fossil fuel stocks are physically exhausted. That is,

²² This rule holds if there is no growth in population and no exogenous technological progress.

²³ This assumes a constant interest rate. With a variable interest rate, the Hartwick rule implies constant consumption but not constant wealth (Lars Svensson 1986).

²⁴ A more detailed analysis of constraints on production functions imposed by minimum material requirements is given by Curt Anderson (1987).

²⁵ Concern about natural resource use and environmental quality also is a recurring theme in the literature (Barnett and Morse 1963).

the present day coal question concerns global climate and its effect on ecosystems rather than the direct cost of coal extraction. Materials balance analysis provides an important conceptual link between resource use and the environment quality: the materials taken from the environment as natural resource inputs to production and consumption are not consumed in a physical sense but are transformed and either remain in the economy as durable goods or recycled inputs, or are emitted back into the environment as waste products (Allen Kneese, Robert Ayres, and Ralph d'Arge 1970). Another environmental impact of nonrenewable resource extraction is the loss of resource amenities—the scientific, recreational, and aesthetic benefits generated by preserved natural environments—when the resource extraction disrupts the natural environment (John Krutilla and Fisher 1985).

Incorporating environmental variables into a capital-resource growth model often requires additional state variables and this can quickly diminish the analytical tractability of the model. The dimensions of the problem can be reduced somewhat if there is a monotonic correspondence between the depletion of the resource stock and the variable that describes the state of the environment.²⁶ For example, if extraction irreversibly depletes the provision of resource amenities, then the environmental impact of extraction can be captured by including the remaining resource stock as an argument of the utility function. Including the resource stock in the utility function creates a stock effect in that marginal extraction

cost—the loss of amenities—increases with cumulative depletion. Consequently, the amenity value of preserved natural environments does lead to less rapid depletion of the resource stock and it can be optimal for cumulative extraction to be less than the initial resource endowment (Krautkraemer 1985).

The optimal level of permanent environmental preservation balances the marginal present value of the resource amenities with the value of the marginal product of the extractive resource. If the resource amenities do not affect the production technology, then they do not affect the conditions for the feasibility or optimality of sustainable or growing consumption. If the marginal value of consumption becomes infinite as consumption goes to zero, and if the marginal value of resource amenities is bounded, then the ability to prevent consumption from decreasing to zero is a necessary condition for permanent preservation. However, even if the asymptotic growth rate of consumption is positive so the marginal value of consumption asymptotically declines to zero, it may not be optimal to permanently preserve any of these natural environments. This is because the sustainable consumption is made possible by unbounded increases in the marginal productivity of the resource brought about by technological progress or capital substitution—the value of the marginal product of the resource is increasing even as the marginal value of output decreases over time (Krautkraemer 1985).

The case for permanent preservation of natural environments is enhanced when production and consumption can be sustained by flows of a substitute for the nonrenewable resource from either renewable resources, or a backstop technology, or if the flow of

²⁶ This is a very simplified view of the relationship between extraction and environmental preservation. In order to capture the ecosystem complexity, several state variables would be necessary. Models with more than two state variables are generally not very tractable and simulation studies may be necessary to discern their properties.

consumption services continues from those natural environments that have been developed (Andrea Beltratti, Graziela Chichilnisky, and Heal 1995; Krautkraemer 1986; Scott Barrett 1992). Since sustainable production and consumption must rely on renewable resources and/or backstop technologies if the average productivity of nonrenewable resources is bounded above, and since the level of consumption provided by renewable resources or backstop technologies does not depend upon the cumulative depletion of the nonrenewable resource, the economy would seek to balance the marginal amenity value of the remaining resource stock with the marginal utility of consumption provided by the substitute in the steady state.

Other cumulative environmental impacts also can be captured as stock effects of nonrenewable resource depletion. For example, the stock of biodiversity might decline monotonically with the cumulative use of extractive resources (although general land degradation rather than that associated with nonrenewable resources is probably a more significant factor in species degradation) and atmospheric carbon accumulation can increase monotonically with fossil fuel depletion, although re-absorption of carbon dioxide by the oceans may make it more appropriate to model the stock of carbon dioxide as slowly degradable rather than strictly accumulative (Hoel and Snorre Kverndokk 1996).

6.2 Critiques of the Neoclassical Model

A good portion of the burgeoning literature on sustainability has been critical of neoclassical economic theory in general, and of the treatment of natural resources in neoclassical economics in particular. Some of this criticism falls under the rubric of ecological economics, although the term ecological eco-

nomics is intended to include the neoclassical paradigm (Robert Costanza 1989).²⁷ Indeed, Dasgupta (1996) "usurps" the name ecological economics to refer to resource and environmental economics combined. Each of the terms neoclassical economics, sustainability, and ecological economics have different meanings for different people, so it is hazardous to categorize them in a discussion of neoclassical growth models. The discussion here will focus on some key issues that have been raised, including the degree of substitutability between reproducible capital and natural capital, intergenerational equity, and uncertainty and irreversibility of environmental degradation. It should be noted that the primary concern of the sustainability and ecological economics literature is the protection of the ecological health of the planet—airsheds, watersheds, biodiversity, global climate—rather than the conservation of particular nonrenewable resources. For example, Ayres (1996) observes, "The limiting factors are less a question of mineral resource availability than scarcity of renewable resources such as forests, topsoil and groundwater, and excessive anthropogenic pressure—or stress—on environmental systems."

A common criticism of the neoclassical growth framework is the claim that reproducible capital and natural capital are complements rather than substitutes in production. For example, fishing boats are used to catch fish rather than to substitute for fish in production (Herman Daly 1994). On the other hand, there are obvious ways in which physical capital can substitute for natural capital. Energy resources can be used to produce insulation and thermal pane windows that will reduce future

²⁷ An overview of ecological economics is provided by Rajaram Krishnan et al. (1995).

energy consumption.²⁸ In addition, more abundant nonrenewable resources or renewable resources can be substituted for scarce nonrenewable resources, as in the case of glass fibers for copper wiring in telecommunications and ceramics and composite materials for metals in the production of various commodities; technological progress can decrease the material content of a particular product, as in the case of aluminum cans;²⁹ and the composition of final output can change to less material intensive commodities. In a capital-resource growth model, if the elasticity of substitution is less than one and inputs are paid the value of their marginal product, then the resource's output share should decline as the capital-resource input ratio increases.

There is not a fixed relationship between output and material input, and empirical indications are that the use of fuel and nonfuel minerals relative to GDP has declined in recent years. For example, the use of steel, aluminum, copper, lead, zinc and nickel in OECD countries has been relatively constant since the mid-1970s as GDP has increased and prices have fallen (Tilton 1989); commercial energy consumption per dollar of GNP in the United States declined by 27 percent from 1971 to 1991 (World Resource Institute 1994); and there is empirical evidence of a structural break in the relationship between metals demand and economic activity during the 1970s (Stephen Labson

1995). There is, of course, a limit to the substitutability of physical capital for fossil fuels or any other nonrenewable resource, and it is not possible for a growing economy to operate on a drop of oil. Thus, any economy would ultimately have to rely upon renewable forms of energy and materials. Sustainability simply is not feasible without some ability to substitute capital or a renewable resource for an essential nonrenewable resource. The ability to substitute physical capital for the life-support services of the environment is, of course, much more limited than the ability to substitute for nonrenewable resources as production inputs.

Concern about limits on the substitution of physical capital for natural capital has led to a distinction between "weak" sustainability and "strong" sustainability. Weak sustainability would maintain intact the productive capacity of the economy, including natural resource assets. The stock of natural capital could be depleted if the depletion was offset by investments in physical or human capital. This is the basic notion of the Hartwick rule, particularly as extended by Dixit, Hammond, and Hoel (1980). Strong sustainability would require keeping the stock of natural capital intact. One difficulty with either type of sustainability is defining an aggregate measure of capital that allows determination of whether or not the capital stock is maintained; this is particularly true for the components of natural capital. Some weighting scheme for aggregating the physical stocks of the various components of natural capital is necessary in order to have one measure of natural capital. Presumably, the relative weights would be based on some appraisal of the relative contribution of the various components toward sustaining the environment and the economy. But then this is just a step

²⁸ Energy resources are a particular focus of some of the ecological economics literature because of the constraints imposed by the laws of thermodynamics. While economists have been criticized for ignoring thermodynamics, it seems that low entropy is the desirable characteristic of energy resources and the nonrenewable resource model itself is a useful framework for examining the economics of non-decreasing entropy.

²⁹ The aluminum content of beverage cans decreased by over one-third between 1964 and 1986 (John Tilton 1989).

away from comparing the relative contribution of natural capital and man-made capital toward sustaining well-being.

Natural capital with a relatively high marginal value should be conserved along an optimal path under either a weak or a strong sustainability criterion. That is, if protection of future welfare is a goal of current decision making and if protection of natural capital is a necessary condition for the protection of future well-being, then imposing an additional constraint on the stock of natural capital is redundant (Dasgupta 1995). However, there is a legitimate concern that not all of the value of natural capital can be appropriated because of the market failures associated with externalities, open access, and the public good nature of resource and environmental amenities. As a consequence, natural capital will be inefficiently over-depleted in the absence of market intervention. An area of agreement between neoclassical resource economics and ecological economics would seem to be that markets undervalue the services of natural capital and that intervention is necessary for efficient management of these resources. Given the difficulty of measuring the value of the environmental services of natural capital, the preservation of physical stocks of natural capital may be a practical step toward sustainability.

Intergenerational equity also plays a large role in discussions of sustainability and ecological economics. Indeed, some argue that sustainability is a matter of equity rather than efficient allocation (for example, Richard Howarth and Norgaard 1991). In a neoclassical growth model, the social rate of time preference is the key parameter that determines future well-being relative to current well-being, so much of the concern about sustainability centers on the

discount rate. The social rate of time preference is a key determinant of the economy's asymptotic growth rate, and it is possible to have a social rate of time preference high enough that consumption eventually declines to zero and the environment is degraded even when it is feasible to have economic growth and environmental preservation.

The social rate of time preference also plays a key role in the conservation of renewable resources. In a steady-state equilibrium, a renewable resource's own rate of interest should equal the social rate of time preference. The resource's own rate of interest includes the marginal growth rate of the resource stock *and* the marginal value of any amenity services generated by the resource stock. The marginal growth rate and the marginal amenity value of the resource can be low enough that the own rate of interest is always less than the social rate of time preference and the resource stock is eventually exhausted (a nonrenewable resource with no amenity value is an example). However, the resource's own rate of interest will be high when the renewable resource provides an essential environmental service with a high marginal value. In this case, the resource should be conserved, perhaps beyond the stock that would maximize the growth or regeneration of the resource. Again, the difference between "should be conserved" and "will be conserved" is critical, since the value of the environmental services may be inappropriable and market failure can lead to environmental degradation and resource depletion, even if the social rate of time preference is low enough that the economy endows future generations with large stocks of private capital assets. Thus, sustainability also is concerned with the mix of assets left to future generations, and market

intervention is necessary to bring about an efficient mix of assets.

A lower social rate of time preference that increases the relative well-being of future generations does not necessarily increase the level of environmental preservation. This is because the lower rate of time preference also increases the demand for capital, and this indirectly increases the demand for extraction. In some cases, the indirect effect can be larger than the direct effect, and environmental preservation declines with a lower rate of time preference (Krautkraemer 1986). A lower discount rate also can spur economic growth which can result in less land allocated for biodiversity preservation (Bob Rowthorn and Brown 1995).

A number of social welfare criteria other than present value maximization have been examined in the neoclassical framework. Sustainability is often defined as nondecreasing utility, and nondecreasing utility has been imposed as a constraint on the optimal use of natural resources (e.g., John Pezzey 1992). Such a constraint effectively prohibits a social rate of time preference that is greater than the asymptotic marginal productivity of capital, and so it prevents the asymptotic decline of the economy when continued growth and environmental preservation are feasible. In other technological settings, it is possible that a nondecreasing utility constraint forces the economy onto a path that is not Pareto-efficient. For example, if consumption relies upon a renewable resource and the initial resource stock is greater than the resource stock that maximizes sustainable yield, there is a time path with decreasing utility that gives greater utility at each point in time than the best extraction path with nondecreasing utility (Krautkraemer and Raymond Batina, forthcoming). The Rawlsian-type crite-

rión that maximizes sustainable consumption also has undesirable outcomes under some conditions. A social welfare criterion that is a weighted average of present value maximization and the asymptotic level of utility is an intriguing alternative (Chichilnisky 1994).³⁰ Given that different social welfare criteria have different outcomes in different technological settings, the desirability of a particular criterion can depend upon one's view of the technological context, a point made by Tjalling Koopmans (1965) with respect to capital growth models.

Uncertainty about the environmental impacts of natural resource use and the possibility that some of those impacts are irreversible has led to the call for the use of a "precautionary principle," or the establishment of a "safe minimum standard." The precautionary principle is that measures to protect the environment should not be delayed by uncertainty about potential environmental damages. The safe minimum standard would call for protection of the environment, particularly the protection of endangered species, unless the costs were unacceptable. Uncertainty and irreversibility have also been a concern of neoclassical resource and environmental economics. Krutilla (1967) argued the case for an "option demand" for environmental preservation in the face of an uncertain future, and subsequent research has identified risk aversion and the expected value of information as a source of option value. The latter concerns the cost of losing the ability to change a decision as new information becomes available. The effect of uncertainty and irreversibility can be quite complex. For example, in the case of demand uncertainty, risk

³⁰ Heal (1997) provides a thorough examination of the Chichilnisky criterion in a variety of alternative settings.

aversion can generate a negative option value for preservation (Richard Hartman and Mark Plummer 1987). The effect of irreversibility also depends upon whether or not the irreversibility constraint is binding; it is possible that the irreversibility of investment in abatement capital can be more significant than irreversibility of an environmental impact. This may be true in the case of global warming (Kolstad 1996).

The precautionary principle and the safe minimum standard would go beyond simply incorporating the effects of risk aversion and the value of future information in a benefit-cost analysis, but exactly what they imply for policy is not clearly defined. To some degree, the safe minimum standard seems intended to deal with uncertainty rather than risk—cases in which even the probabilities of various outcomes are uncertain. In addition, it places the burden of proof on environmental degradation rather than environmental protection. Nevertheless, a determination of what constitutes “unacceptable” costs of environmental protection seems to be a necessary step if the safe minimum standard is to be an operational concept.

The method of environmental evaluation is another concern raised in some critiques of neoclassical economics. The ecological economics literature takes issue with the neoclassical approach of taking individual preferences as given and using them as the basis for social valuation. Instead, some of this literature takes the view that preferences are socially determined and may be a large part of the environmental problem, and therefore cultural changes are desirable in order to achieve sustainability. For example, Peter Söderbaum (1994) writes, “. . . attempts to measure the tastes of consumers or willingness to pay in actual or hypothetical markets

are not very productive if those tastes or values and corresponding life styles are unsustainable in the sense that they systematically contribute to a degraded environment.” Since individual preferences play a fundamental role in neoclassical economics, the role of consumer sovereignty in social decision making is an area of disagreement between ecological economics and neoclassical economics that is unlikely to be resolved.³¹

6.3 *Nonrenewable Resources and National Income Accounting*

National income accounts are often taken as at least a rough measure of an economy's income and/or well-being. It seems desirable, then, that these measures would capture the economic impact of changing resource scarcity. Most discussions of natural resource and environmental accounting note that the Hicksian definition of income incorporates the notion of sustainable income. Indeed, the definition of income as the amount of consumption that can occur without depleting one's wealth is not unlike the definition of sustainability as meeting the needs of the present without harming the ability of future generations to meet their needs (World Commission on Economic Development 1987).

The current treatment of nonrenewable resources is to include as profit the entire net return from resource extraction when some of the calculated profit is actually the user cost associated with the resource stock and represents asset depletion rather than income. Ideally, nonrenewable resource depletion should be treated like capital depreciation; this would change the

³¹ If individual preferences are not the starting point for a society's allocation of resources, then some determination must be made of whose preferences are the starting point.

composition, but not the level, of gross domestic product, and it would reduce net domestic product. However, the current treatment of nonrenewable resources also excludes from national income the value of reserve additions resulting from exploration and development activities. Resource depletion was included in U.S. national accounts until 1947 when it was removed because additions were not included (Steven Landefeld and Carol Carson 1994b). An additional shortcoming of the national income accounts is that the costs of extraction are undervalued and so the net return to extraction is overvalued to the extent that resource extraction results in uncompensated environmental damage. That is, some of the value added assigned to the profits of mining companies should be an imputed value-added assigned to environmental services (Raymond Prince and Patrice Gordon 1994).

Under certain simplifying assumptions, the proper treatment of nonrenewable resource depletion in the national income accounts is relatively straightforward. In the case of perfect foresight and present value maximization with a constant interest rate, net national product is just the normalized current value Hamiltonian along the optimal path and represents, "... what might be called the stationary equivalent of future consumption..." (Martin Weitzman 1976).³² In this context, the proper calculation of net national product is the sum of consumption and the value of net investment, including the value of net changes in the stocks of reproducible, human, and natural capital. The changes in capital stocks should be valued at their respective marginal net value or price less marginal cost in

the case of a nonrenewable resource. As discussed above, market information about *in situ* values is not generally available. The Bureau of Economic Analysis uses a variety of methods for estimating the resource rent (Landefeld and Carson 1994a).

An alternative approach to estimating the value of nonrenewable resource depletion is the sinking fund approach taken by Salah El Serafy (1989). This method determines the amount of extractive net revenue that can be considered true income by equating the present value of the revenue stream generated by extraction over the life of the mine with the present value of the maximum level of income those revenues can sustain in perpetuity. The remainder of the resource revenue must be reinvested in order to make up for eventual resource exhaustion. The simplest case assumes that the current resource price, extraction cost, rate of extraction, and interest rate will continue into the future until the resource is exhausted. The life of the mine, denoted n , is given by $n = S/q$, where S denotes current reserves and q denotes current extraction. If R denotes the net revenue from the nonrenewable resource, and X denotes true income, then

$$\sum_0^n \frac{R}{(1+r)^t} = \sum_0^\infty \frac{X}{(1+r)^t} \quad (15)$$

where r denotes the rate of interest. Then

$$X = R \left[1 - \frac{1}{(1+r)^{n+1}} \right] \quad (16)$$

The depletion charge for the reduction in the nonrenewable asset is $R-X$. This depletion charge can be calculated on the basis of current values only, although this is due to the assumption that resource price, extraction cost, and

³² However, this level of consumption cannot necessarily be maintained forever if the interest rate is falling over time (Asheim 1994).

extraction rate are stationary.³³ Additions to reserves would be handled by increasing n , the life of the reserves.

The inclusion of capital gains in national income depends upon whether or not the capital gain was anticipated and the intended purpose of the accounts. With perfect foresight in a closed economy, any capital gains are anticipated and capitalized into the current value of the resource asset so that capital gains are not included in net national product. In the case of an open economy, the national wealth can be kept constant if the capital gains on an exported resource are consumed each year and capital gains should be included in net national product.³⁴

Since *in situ* value is a function of the entire expected price path and future extraction cost, unanticipated discoveries and technological developments, or even unanticipated changes in market structure, can cause unanticipated changes in the value of a given resource stock. Unanticipated capital gains could be consumed without decreasing the value of assets at the beginning of the period and so could be construed to be income. A more forward looking view would recognize that the additional consumption afforded by the unanticipated capital gain may not be sustainable. The correct treatment of revaluations of the resource stock can depend upon whether the purpose of net national product is to measure changes in future productive capacity or the level of consumption that can be sustained

over time (David Bradford 1990). Nonrenewable resource prices can be quite volatile, and wide fluctuations in net national product could be caused by including revaluations of nonrenewable resource assets. For example, there are years in the last two decades where changes in the value of Norwegian petroleum reserves exceed the value of conventionally measured gross domestic product (Aaheim and Nyborg 1995). Changes in price and extraction costs also can affect the physical measure of the resource stock since reserves generally are defined in terms of whether or not they are economically recoverable.

There have been some attempts to incorporate natural resource depletion into national income accounts. For example, Indonesian GDP grew at an annual rate of 7.1 percent over the period 1971–84 but when depletion charges for petroleum, timber, and soils are taken, the annual growth rate for NDP is only 4.0 percent (Robert Repetto et al. 1989). Including petroleum reserve depletion in the national accounts of the United States in 1978 would have reduced net national product by 1.1 percent (Hartwick and Hageman 1993). However, overall additions to mineral reserves in the United States have kept pace with depletion of those reserves over a thirty-year period. Estimates of the value of mineral reserves in the United States in constant 1987 dollars range from \$554–1,077 billion for 1958 and \$530–1,030 for 1991 (Landefeld and Carson 1994a).³⁵

Expenditures to prevent environmental damage from mineral extraction are intermediate business expenditures

³³ A constant extraction path and constant price are incompatible with the Hotelling rule (Asbjorn Aaheim and Karine Nyborg 1995) although the El Serafy method can give a reasonable estimate of the optimally calculated depletion charge, at least in some cases (Hartwick and Anja Hageman 1993).

³⁴ However, positive capital gains in the world economy as a whole indicate the interest rate is decreasing and constant wealth does not imply constant consumption (Asheim 1996).

³⁵ The minerals are petroleum, natural gas, coal, uranium, iron ore, copper, lead, zinc, gold, silver, molybdenum, phosphate, sulfur, boron, diatomite, gypsum and potash. The bulk of mineral production is accounted for by petroleum and natural gas.

and so are not counted in either gross or net domestic product. Mining profit is higher if firms are able to use the environment rather than making preventive expenditures, and so GDP and NDP will be overestimated if there is no charge for environmental degradation caused by nonrenewable resource use. Incorporating the effect of nonrenewable resource extraction on environmental assets in the national income accounts is a substantially more difficult task than incorporating nonrenewable resource depletion. There is little market data concerning the value of environmental assets, and methods for estimating these values can be controversial.³⁶ Estimates of the cost of maintaining a given level of environmental quality have been used to value environmental degradation. If the value of environmental degradation is estimated by the expenditures necessary to maintain environmental quality, then environmental degradation for the U.S. from economic activity as a whole was relatively constant at 1 percent of GDP in the 1980s, and air and water quality indices showed improvement over that period (Prince and Gordon 1994). Moreover, the national income accounts also do not capture future technological progress, and the impact of technological progress on the use of national income as a measure of sustainability may far outweigh the impact of adjustments for environmental degradation (Weitzman and Karl-Gustaf Löfgren 1997).

7. Conclusion

Finite availability is perhaps the defining characteristic of a nonrenewable resource and generates the "Hotelling

rule" that the marginal value of a nonrenewable resource stock increases at the rate of interest. However, many other factors, including exploration, capital investment, and heterogeneous ore quality are also important to the economics of nonrenewable resource depletion. The investigation of how these other factors affect the empirical implications of the Hotelling model has been spurred by the frequent failure of the basic Hotelling model to explain the observed dynamic behavior of nonrenewable resource prices and in situ values. These other factors can affect price and depletion paths in a number of ways, particularly when considered in combination with each other. The variety of possible outcomes makes it difficult, if not impossible, to make any general predictions about the overall impact on price and extraction paths. These other factors, particularly the discovery of new deposits and technological progress that lowers the cost of extracting and processing nonrenewable resources, appear to have played a relatively greater role than finite availability in determining observed empirical outcomes.

While models that include these other factors have improved the empirical performance of the Hotelling model, they have not completely reconciled the economic theory of nonrenewable resources with the observed data. The distinction between the response of nonrenewable resource prices and in situ values to anticipated changes in extraction cost, interest rate, reserve discoveries, availability of backstop substitutes, etc., and the response to unanticipated changes in those variables with the arrival of new information is important and is likely to play a greater role in future empirical research. The observed time paths for the resource price and in situ value may represent a

³⁶ This is particularly true of contingent valuation. See Paul Fortney (1994) for an overview of the debate over the use of contingent valuation.

combination of the initial portion of many different expected price paths rather than outcomes along one fully anticipated price path. It isn't obvious how unanticipated price changes will be incorporated into empirical work, and such empirical investigations probably would demand greater information and likely would have to be tailored to the specific circumstances of individual nonrenewable resources. Although unanticipated changes would not necessarily have a particular bias, it does seem to be a recurring tendency to overestimate the imminence of nonrenewable resource exhaustion.

The empirical evidence also indicates that the discovery of new deposits and technological progress have significantly mitigated the impacts of finite availability on the relative scarcity of nonrenewable resources used in commodity production. The finite availability of a nonrenewable resource at a particular point in time has not yet led to increasing economic scarcity of nonrenewable resources for production and consumption activities. The development of new materials that substitute for nonrenewable resources, improvements in extraction and processing technologies that allow the economical use of low grade ores, and the greater efficiency of use of nonrenewable resources are all likely to continue. The future is uncertain, and whether or not these mitigating factors will keep pace with increased demand for nonrenewable resources from a growing population and economic development remains to be seen. In any case, a more pressing concern is the protection of the nonrenewable and renewable environmental resources that provide the basic life support services and generate a wide variety of amenity services, particularly since it is not likely that substitutes can be found for the basic life

support services of the natural environment. Given the open access and public good nature of these resources and services, market interventions are necessary to prevent inefficient use of these resources. Because of this, the attention focused on the environmental impacts of nonrenewable resource use will continue to increase with increased emphasis on the details of ecological interactions and the management of global public assets.

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