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ABSTRACT

A model is devised to test for the existence and estimate the magnitude of monopoly and differential (or Ricardian) rent in a nonrenewable natural resource industry. The model, which is based on a flexible cost function, is quantified and estimated for the U.S. copper industry. The empirical results indicate that substantial differential rent is being earned by the domestic copper producers. In contrast, even though in the past higher market concentration has been associated with higher prices, little evidence supports the conclusion that monopoly rents are accruing to the industry today.

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I: INTRODUCTION

Economic rent is defined as any payment to a factor of production in excess of its supply price. Much of the interest in economic rent stems from the fact that it can be taxed away without affecting either the supply of inputs or the production of output. However, the ease with which a taxation scheme can be implemented depends on the type of rent earned. For nonrenewable natural resource industries, three types of rent are of particular importance: monopoly rent, which is due to the high concentration of sellers in many of these markets; differential or Ricardian rent [Ricardo 1817], which is due to the differing quality of natural-resource deposits; and scarcity rent [Hotelling 1931], which is due to the finite nature of the natural resource base. Recent empirical investigations of rent in natural resource industries have concentrated on the implications of scarcity rent [Feige and Geweke 1979, Heal and Barrow 1980, and Smith 1979, for example]. In this paper, monopoly and differential or Ricardian rent are investigated. A general model, based on a flexible cost function, is derived to test for the existence of the two types of rent. The model is then quantified and estimated for the U.S. copper industry. The organization of the paper is as follows. In the next section, the types of economic rent are discussed. In sections III and IV, the estimating equations are derived and empirical results are presented. And finally, in section V, conclusions are drawn and the implications of the empirical findings for taxation of rent in the copper industry are discussed.

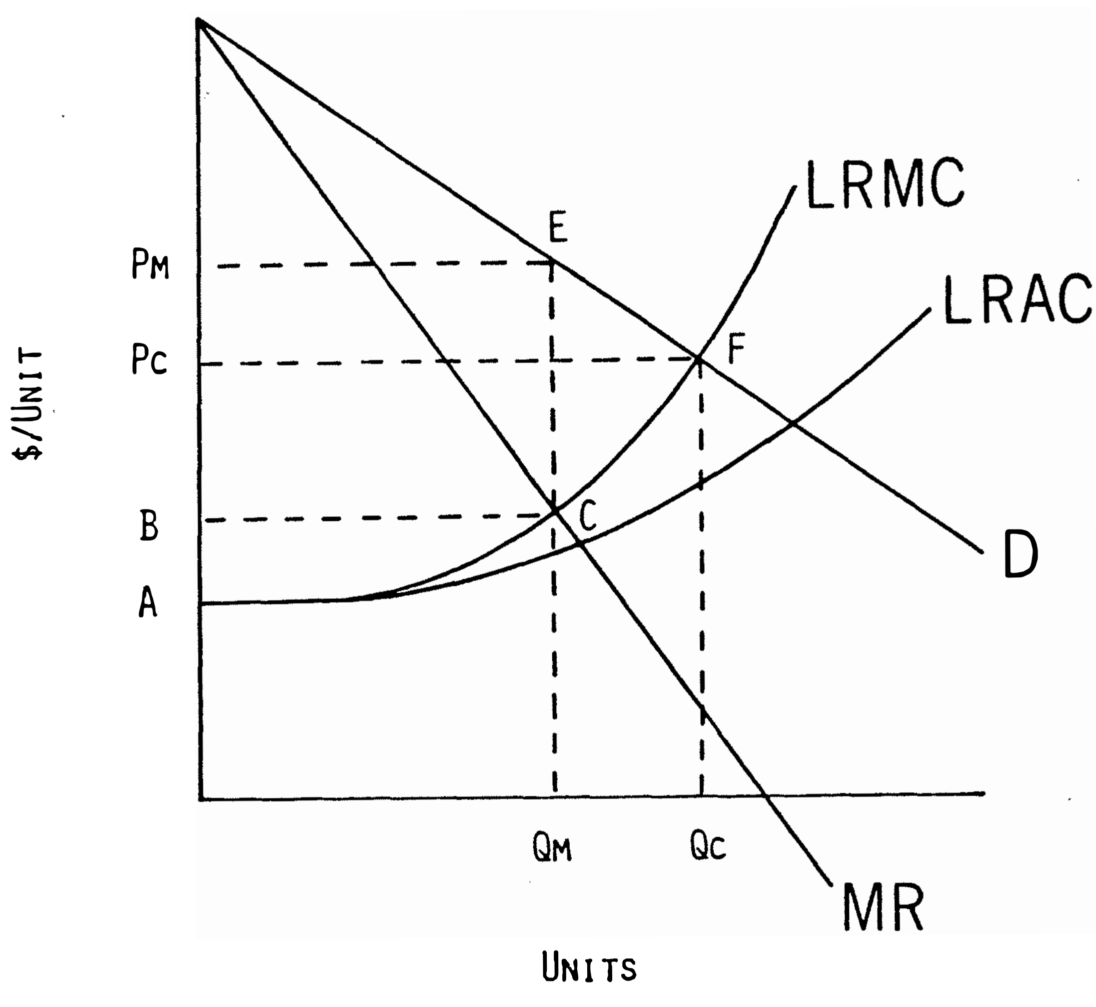
II: TYPES OF RENT

The theory of exhaustible resources first developed by Hotelling is well known. A nonrenewable natural resource commodity will earn a positive scarcity rent, and, if the commodity is produced in a competitive market, in long-run equilibrium, price will equal marginal extraction cost plus scarcity rent. The deviation of price from marginal extraction cost reflects the user cost of each additional unit produced (i.e., the marginal loss in profits from future extraction due to a unit extracted today) and will occur in an industry where all deposits are of the same quality (i.e., where marginal extraction costs are constant) as well as in an industry where marginal costs rise with cumulative production. However, there are several reasons why scarcity rents may be small in the copper industry. In general, scarcity rents are negatively related to the size of the resource stock. In the copper industry over the last 25 years, the discovery rate for new deposits has been greater than the rate at which deposits have been used up. That is, the ratio of known resources to annual consumption has actually risen, which should imply a fall in scarcity rent. In addition, the larger the increase in marginal extraction cost over time, the smaller the increase in scarcity rent. And, in fact, scarcity rents actually decrease if the rate of growth of extraction costs exceeds the discount rate times the ratio of scarcity rent to extraction cost [Hanson 1980], a very likely possibility for the copper industry. For these reasons, in deriving the model and estimating equations in the next two sections, scarcity rents will be ignored. However, the concept of scarcity rent is reintroduced in section IV: 3, where a model that is consistent with the existence of sizable scarcity rents is reviewed, and the statistical implications of ignoring scarcity rents in the model derived here are discussed.

Differential or Ricardian rents are not payments for the exhaustion of a resource stock. They arise because ore deposits of most minerals are of varying quality and production cost depends on deposit characteristics.[1] Some of the most important characteristics are: grade, the percent of metal contained in ore in the ground; deposit size, shape, and depth, whether ore tonnage is large or small and near-surface or deeply buried; deposit mineralogy and geochemistry, the way in which the metal is chemically combined with other elements; and deposit location, distance from convenient transportation and other infrastructure. In the theoretical literature on exhaustible resources, it is often assumed that only one quality of deposit will be mined at any time and that the shift to lower quality ores will occur only after the higher quality ores have been depleted [see Herfindahl 1967, for example]. However, in practice, deposits of many qualities are mined simultaneously for several reasons. With an integrated mine-through-refinery operation, there may be an optimal lifetime for the mine. If the deposit is exploited too rapidly, an overly large processing facility is required that will be without ores to process when the deposit is depleted. In addition, ore quality varies within a deposit. For example, low-quality near-surface ores in a strip mine may have to be mined before the high-quality ores are uncovered. If marginal deposits are mined when demand is high but not when demand is low, production can expand only by incurring higher costs, and these cost differentials persist in the long run. Such an industry is characterized by increasing costs; that is, its long-run average cost (LRAC) curve slopes upwards. If a mineral commodity is produced in a competitive market under conditions of rising LRAC, long-run equilibrium price will equal long-run marginal cost (LRMC), which will be greater than LRAC. This situation is shown in figure 1, where competitive output Qc is being produced and sold at competitive price Pc. The marginal deposit is earning no rent, but low-cost deposits are earning differential rent equal to area ACFPc.

FIGURE 1

DETERMINATION OF DIFFERENTIAL AND MONOPOLY RENT



Because many mineral industries are characterized by a high degree of market concentration and vertical integration, monopoly rents may be earned. High concentration is often due to economies of scale, high capital requirements, and the absolute cost advantage of controlling scarce natural resources. Vertical integration takes place when metal manufacturing (refining and smelting) firms integrate backwards into mining, in order to obtain secure ore supplies, or forwards into semifabricating. For example, in the United States in 1972, four- and eight-firm concentration ratios for primary copper manufacturing were 72 and 98 percent respectively [U.S. Bureau of the Census 1975], and the ratios for copper mining and milling were 69 and 87 percent [Slade 1979]. All the major primary-copper manufacturing firms are at least partially integrated into mining.[2] In such concentrated markets, the competitive marginal-cost pricing model is not apt to apply, and an oligopoly or monopoly model should be more appropriate. In figure 1, the monopoly output Qm is determined by the intersection of marginal revenue (MR) and LRMC; Qm is sold at the monopoly price Pm.[3] As in the previous example, the marginal deposit is earning no differential rent. However, because Qm is less than Qc, the differential rent earned by the low-cost deposits has decreased to area ACB. Monopoly rent, equal to area BCEPm in the figure, is now accruing to the industry.

In the next section, a model is derived that enables us to test for the existence and estimate the magnitude of monopoly and differential rent in a nonrenewable natural resource industry.

III: THEORETICAL MODEL

If we assume that, in the long run, the output of a nonrenewable natural resource industry can expand without affecting the prices of factors other than land (or ore deposits), then the only reason for the industry LRAC curve to slope upwards is the nonhomogeneous nature of ore deposits.[4] If, in addition, we assume that no alternative uses exist for land used for mining, then all payments to land are rent.[5]

In order to estimate the industry long-run marginal and average cost schedules, we must make some specific assumptions about the form of the cost curves. Suppose that the industry cost curve is homothetic and linearly homogeneous in the prices of inputs other than land,

$$TC = f(Q)\ c(p,T) \tag{1}$$

where TC is total cost

Q is industry output

$p = (p_i)$ is a vector of input prices

and T is a technology or productivity index.

For c(..) a flexible form should be used because it provides a local second-order approximation to an arbitrary twice continuously differentiable function. The transcendental logarithmic (translog) cost function [Christensen, Jorgenson, and Lau 1971] is used here.

$$\ln c = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln p_i + 1/2 \sum_{j=1}^{n} \sum_{i=1}^{n} \gamma_{ij} \ln p_i \ln p_j + \alpha_T \ln T + 1/2\, \gamma_{TT} (\ln T)^2 + \sum_{i=1}^{n} \gamma_{Ti} \ln T \ln p_i \tag{2}$$

where $\gamma_{ij} = \gamma_{ji}$.

To insure linear homogeneity in prices, the following restrictions must hold.

$$\sum_{i=1}^{n} \alpha_i = 1, \qquad \sum_{i=1}^{n} \gamma_{ij} = 0, \; j = 1,\ldots,n$$

and $$\sum_{i=1}^{n} \gamma_{Ti} = 0. \tag{3}$$

Define the elasticity of total cost with respect to output, η, by

$$\eta = dTC/dQ \; Q/TC = MC/AC. \tag{4}$$

If η is constant, then marginal cost (MC) is a constant multiple of average cost (AC)

$$MC = \eta AC \tag{5}$$

For η to be constant, f(.) must assume the simple form, $f(Q) = aQ^{\eta}$, where a is a constant or a function that does not depend on Q. With this simple functional form for f(.), the cost function is not only homothetic, it is homogeneous of degree η.

As deposits are depleted, the cost function will shift upwards; therefore, in the long-run, f will be a function of cumulative production as well as of current production. If we assume that the relationship between cost and cumulative production is multiplicative, then f becomes

$$f(Q,\overline{Q}) = aQ^{\eta} \, \overline{Q}^{\,\delta} \tag{6}$$

where

$$\overline{Q} = \int_{-\infty}^{t} Q_{\tau} d\tau. \tag{7}$$

[6]

Combining these results we have[7]

$$\ln TC = \ln a + \eta \ln Q + \delta \ln \overline{Q} + \ln c$$

and $$\ln AC = \ln a + (\eta - 1) \ln Q + \delta \ln \overline{Q} + \ln c. \tag{8}$$

A monopolist, producing a nonrenewable natural resource commodity and facing a downward-sloping demand curve Q(P), will choose Q to maximize profit, -

$$\max_{Q} - = P \cdot Q(P) - TC.$$

The first-order condition for profit maximization is

$$d\pi/dQ = P + Q \cdot dP/dQ - MC = 0$$

$$P\ (1 + dP/dQ \cdot Q/P) = MC$$

$$P\ (1 - 1/\xi) = MC$$

or $$P = MC\ [1 + 1/(\xi - 1)] = MC\ (1 + m) \qquad (9)$$

where ξ is the elasticity of demand for the mineral commodity

and m is the monopoly markup over marginal cost.

Combining (2), (5), (6) and (9), we have

$$P = (1 + m)\ MC = \eta(1 + m)\ AC = \eta(1 + m)\ a\ Q^{\eta-1}\ \bar{Q}^{\delta}\ \ c(p,T)$$

and $$\ln P = \alpha + (\eta - 1)\ \ln Q + \delta\ \ln\bar{Q} + \sum_{i=1}^{n} \alpha_i \ln p_i + 1/2 \sum_{j=1}^{n} \sum_{i=1}^{n} \gamma_{ij} \ln p_i \ln p_j$$

$$+ \alpha_T \ln T + 1/2\ \gamma_{TT}\ (\ln T)^2 + \sum_{i=1}^{n} \gamma_{Ti} \ln T \ln p_i \qquad (10)$$

where $\alpha = \ln[\eta(1 + m)\ a\ e^{\alpha o}\ ]$.

Equation 10 will form the basis for the empirical tests of economic rent in the copper industry. If η, the elasticity of total cost, is greater than one ($\eta-1 > 0$), the industry is characterized by increasing costs and differential rent is being earned. If m, the monopoly markup over marginal cost, is positive, monopoly rent is accruing to the industry.

IV: EMPIRICAL RESULTS

IV:1 Differential Rent

If there are only two factors of production other than land—capital and labor, with prices r and w respectively—then, when restrictions (3) are substituted into (10), we have

$$\ln P = \alpha + (\eta - 1)\ln Q + \delta \ln\bar{Q} + \alpha_w \ln w + (1 - \alpha_w)\ln r + 1/2\gamma_{ww}(\ln w)^2 + 1/2\gamma_{ww}(\ln r)^2 - \gamma_{ww}\ln w \ln r + \alpha_T \ln T + 1/2\gamma_{TT}(\ln T)^2 + \gamma_{Tw}\ln T \ln w - \gamma_{Tw}\ln T \ln r.$$

which, after algebriac simplification, becomes

$$\ln(P/r)_t = \alpha + (\eta - 1)\ln Q_t + \delta \ln\bar{Q}_t + \alpha_w \ln(w/r)_t + 1/2\gamma_{ww}[\ln(w/r)_t]^2 + \alpha_T \ln T_t + 1/2\gamma_{TT}(\ln T_t)^2 + \gamma_{Tw}\ln T_t \ln(w/r)_t + v_t$$

$$v \sim N(0, \sigma_v^2). \qquad (11)$$

The error term v was added to equation 11 because price cannot be controlled exactly by the monopolist.[8] Because price and output are jointly determined by the monopolist, instruments were used for ln Q in estimating all the equations in tables I and II.[9,10]

The data consist of annual time-series observations for the U.S. copper industry during the 1947-1978 period. The data on price, output, wages, and interest rates are discussed in the data appendix. For the first estimate of the cost function, an index of labor productivity in copper mining was used for T. This index is also discussed in the appendix. The resulting estimate of $\eta - 1$ is shown in the first row of table I. In the table, t-ratios are given in parentheses under the corresponding estimated coefficients.

The estimated coefficient, $\eta - 1$, is both positive and statistically significant at the 95 percent level of confidence. However, we cannot yet conclude

TABLE I: ESTIMATES OF $\eta - 1$

Equation	Years	Production Function	T	$\hat{\eta} - 1$ Coef of $\ln \hat{Q}$	R^2	DW	F	Estimation Technique[a]
1	1947–1978	Full	Labor Prod.	.29 (1.9)	.87	1.3	29	IV
2	1947–1978	No $\Delta w/r$	Labor Prod.	.24 (1.5)	.68	2.0	19	TSCO
3	1870–1978	No $\Delta w/r$	e^t	.26 (4.0)	.80	1.7	139	TSCO
4	1870–1978 Equilibrium Years	No $\Delta w/r$	e^t	.20 (1.8)	.77	1.9	58	IV

a) IV indicates that the equation was estimated by the method of instrumental variables.

TSCO indicates that a two-stage Cochrane-Orcutt technique [Hall, 1976] was used. This technique corrects for first-order serial correlation of the error term.

that differential rent is being earned in the copper industry. The positive coefficient of $\hat{\ln Q}$ may merely indicate that marginal costs rise as capacity constraints are approached. The copper industry has not been characterized by rapid growth, and we can assume that, in most years, capacity is at its desired level. However, with random fluctuations in supply and demand, price will be determined by the short-run (not the long-run) marginal cost curve. To estimate the long-run cost curve, we must look at years that can be considered "equilibrium" years. Herfindahl [1959] identified years in the 1870-1957 period when demand or supply was distorted from anticipated long-run levels. I have examined the 1958-78 period and used the same criteria to discard unusual years (i.e., years when there were major strikes, commodity booms, etc.) In order to estimate a cost function using only equilibrium years, it is necessary to go back farther in time to obtain sufficient observations. Unfortunately, data on factor prices were not available prior to 1947. Therefore, another simplifying assumption was made. We assume that, in the last century, changes in the ratio of factor prices, w/r, have been small relative to changes in technology. If w/r is constant, equation 11 becomes[11]

$$\ln P_t = \alpha' + (\eta - 1)\ \ln Q_t + \ \delta \ln \bar{Q}_t + \alpha_T'\ \ln T_t + 1/2\gamma_{TT}\ (\ln T_t)^2 + v_t \qquad (12)$$

The second row of table I shows the value of $\eta \hat{-} 1$ obtained by estimating the cost function with w/r held constant using data from the 1947-1978 period (the period used in estimating the first equation in the table). This equation is included to show that holding w/r constant does not change $\eta \hat{-} 1$ very much.

To obtain long-run estimates of η-1, annual time-series data for the 1870-1978 period were used. Data on labor productivity in copper mining are also not available prior to 1947. Therefore, e^t was used as the productivity index, T.[12] Rows 3 and 4 of table I show estimates of η-1 obtained using annual observations for all years and for equilibrium years, respectively. We can see that the magnitude of $\hat{\eta-1}$ is reduced when only equlibrium years are considered, but $\hat{\eta-1}$ is still positive and statistically significant at the 95 percent level of confidence. We can therefore conclude that the positive estimated coefficient of $\ln\hat{Q}$ is not due to short-run capacity constraints but is an indication that the long-run average cost curve slopes upward and that differential rent is being earned in the copper industry.

IV:2 Monopoly Rent

In equations 10-12, the constant term is a function of m, the monopoly markup over cost. Thus far we have assumed that m is constant. However, if the market power of the U.S. copper producers changed significantly in the last century, the monopoly markup may vary with time. One measure of potential market power is the n-firm concentration ratio, CRn. Suppose that (1 + m) is a multiplicative function of CRn,

$$(1 + m)_t = \beta_0 \, CRn_t^{\beta}.$$

Then α', the constant term in equation 12, becomes

$$\alpha'_t = \ln(1 + m)_t + c_1 \qquad (c_1 \text{ a constant})$$

$$= \ln\beta_0 + \beta \ln CRn_t + c_1 \,. \qquad (13)$$

If changes in industry concentration have led to changes in the monopoly markup, we can expect $\hat{\beta}$ to be positive and statistically significant. In estimating the cost function with α' replaced by α'_t (as defined by equation 13), the eight-firm concentration ratio in copper mining was used for CRn (see data appendix). Again, e^t was used as a productivity index.

The first equation in table II shows estimates of β and $\eta - 1$ obtained using annual data from the 1911-1978 period.[13] $\hat{\beta}$ is both positive and statistically significant at the 95 percent confidence level. We can therefore conclude that increases in industry concentration have been associated with price increases. However, caution should be used in interpreting these results. The finding that higher concentration is associated with higher prices does not necessarily imply that large monopoly rents are being earned by the copper producers today. Much of the variation in U.S. concentration ratios occurred in the earlier part of the 1911-1978 period when the world copper industry was highly concentrated. In the last few decades, many copper-producing countries nationalized their deposits, leading to a dramatic decline in world copper-industry concentration.[14] Today, the world copper industry is generally considered to be competitive. Most copper outside the United States is sold under long-term contracts at prices based on the London Metal Exchange (LME) price, a competitively determined price.[15] Between 1970 and 1978, the average of the U.S. producer price was 62 cents per pound, whereas the average of the LME price was 64 cents per pound. If anything, costs in the United States are higher than costs abroad. Therefore, significant monopoly rents probably were not earned by the U.S. copper producers in the last decade.

To test the hypothesis that the relationship between copper-industry - centration and price has changed in recent years, two additional equations were estimated, one for the period prior to 1954 and one for 1954 and later years.[16] The second and third equations in table II show that $\hat{\beta}$ is positive and significant in the earlier period equation but negative and insignificant in the later period equation, confirming the hypothesis that the price-concentration relationship changed. If the price-concentration relationship has changed in recent years, we might question the stability of the cost function as a whole.

TABLE II: ESTIMATES OF β AND $\eta - 1$

Equation	Years	$\hat{\beta}$ Coef of lnCR8	$\widehat{\eta - 1}$ Coef of $\ln\hat{Q}$	R^2	DW	F	Estimation[a] Technique
1	1911–1978	.80 (1.7)	.21 (1.9)	.77	1.6	50	TSCO
2	1911–1953	.77 (1.9)	.29 (3.5)	.79	1.6	35	TSCO
3	1954–1978	–1.6 (–1.2)	.31 (1.3)	.47	1.7	4	TSCO

a) See page 11.

However, when the Quandt log-likelihood ratio [Quandt 1960] was applied to test the null hypothesis

$$HO: \{\alpha_1^* = \alpha_2^*, \beta_1 = \beta_2, (\eta - 1)_1 = (\eta - 1)_2, \alpha T_1', = \alpha T_2',$$

$$\gamma TT_1 = \gamma TT_2, \rho 1 = \rho 2\}$$

(where the subscripts 1 and 2 apply to the first and second periods, re- tively, and ρ is the first-order autocorrelation coefficient of the error term), the null hypothesis could not be rejected at the 90 percent level of confidence. Therefore, no evidence leads to the conclusion that the cost function changed between the two periods of interest.

IV:3 Scarcity Rent

Heal and Barrow [1979] developed a model to explain long-run price movements of natural resource commodities. The model is based on the assumption that the supply of and demand for natural resource commodities depends not only on current price, but also on the rate of capital gain on the mineral commodity compared to the rate of return available from other assets. The Heal-Barrow model does not test for the existence or estimate the magnitude of scarcity rents, but it is in the spirit of the theory of exhaustible resources developed by Hotelling. One of the equations tested by Heal and Barrow is of the form

$$\dot{P}/P_t = a_0 + a_1 \dot{P}/P_{t-1} + a_2 \dot{P}/P_{t-2} + a_3 r_t + a_4 r_{t-1} + a_5 r_{t-2} + a_6 \dot{MC}/MC_t + a_7 \dot{MC}/MC_{t-1} + a_8 \dot{MC}/MC_{t-2} + \varepsilon_t . \quad (14)$$

In equation 14, $\cdot$ denotes the time rate of change of a variable. $\dot{P}/P$ is thus the rate of return on the natural resource commodity and r is the rate of return on some other asset.[17] Equation 14 can be estimated with MC replaced by the marginal cost function derived earlier. If

$$\ln MC_t = \alpha + (\eta - 1)\ln Q_t + \delta \ln \bar{Q}_t + \alpha_t' t + 1/2\, \gamma_{tt} t^2,$$

then $$\dot{MC}/MC_t = (\eta - 1)\,\dot{Q}/Q_t + \delta \dot{\bar{Q}}/\bar{Q} + \alpha_t' + \gamma_{tt}\, t. \qquad (15)$$

When equation 14 was estimated with marginal cost defined by 15, two of the interest rate variables were statistically significant at the 95 percent confidence level.[18] In addition, the coefficients of the interest rate variables summed to zero, a result also obtained by Heal and Barrow, who noted that it implies that the rate of change, not the level of interest rates influences $\dot{P}/P$.[19] The finding that the level of interest rates does not influence the rate of change of copper prices does not contradict the standard Hotelling-type theory. However, it is consistent with a simpler theory of pricing and cost. For example, in equation 11, which can be rewritten as

$$\ln P_t = \ln r_t + G(Q, \bar{Q}, w/r, T), \qquad (11')$$

scarcity rents are assumed to be negligible. If we differentiate (11') with respect to t, we obtain

$$\dot{P}/P_t = \dot{r}/r_t + dG/dt.$$

The rate of change of copper prices is related to the rate of change of interest rates.[20]

The analysis of this section does not in any way demonstrate that scarcity rents are small in the copper industry. It is therefore worth discussing the statistical implications of neglecting scarcity rents in the equations estimated in earlier sections. The equations shown in tables I and II were based on the assumption that

$$MR_t = MC_t.$$

If instead,

$$MR_t = MC_t + rent_t,$$

where scarcity rents are not negligible, the earlier equations are misspecified. However, as long as we know whether the coefficients of the cost function are positively or negatively correlated with scarcity rent, we know the direction of the bias of their estimated coefficients. In particular, holding all else constant, an increase in scarcity rent implies a fall in output. Therefore, the bias in the estimate of $\eta - 1$ is negative, $\hat{\eta} - 1$ is biased towards zero, and the results reported earlier are conservative.[21]

V: SUMMARY AND CONCLUSIONS

The empirical tests for differential or Ricardian rent in the U.S. copper industry revealed that the industry long-run average cost curve is upward sloping and that differential rent is being earned. The empirical estimates of η, the elasticity of total cost with respect to output, imply that average extraction and processing cost is approximately 20 percent below the cost of producing from the marginal mine. This estimate is in line with the findings of Knight and Davies [1978], who used engineering data to estimate unit production costs for the major western-world copper mines; they found the cost of the median mine to be 30 percent below the cost of the marginal mine.[22] If average and marginal costs differ by 20 percent, then, at 1978 price and output levels, the U.S. industry earned approximately half a billion dollars in differential rent. If land had no alternative use, this sum could be taxed away without affecting production. However, implementing such a scheme would be extremely difficult because it would require accurate knowledge of extraction costs on a deposit-by-deposit basis. Even if these costs were known at a particular time, mining costs change as different parts of ore bodies are worked. In addition, the statement that rent "could" be taxed does not imply that it "should" be taxed.

If all differential rent were appropriated, producers would have no incentive to use resources efficiently (to produce from the most economical sources).

The empirical tests of monopoly rent in the U.S. copper industry revealed that, during the last century, increases in industry concentration have been associated with higher prices. We cannot conclude, however, that large monopoly rents are being earned in the industry today. In the 1970's, the mean of the U.S. producer price of copper was below the mean of the LME price, a competitively determined price, and, if anything, costs in the United States were higher than costs abroad. Therefore, U.S. copper producers probably did not earn significant monopoly rents in the last decade.

FOOTNOTES

1 Although Ricardo mentioned minerals, his analysis was primarily about land, which varies in quality but is not exhausted through proper use.

2 With the exception of firms like ASARCO that are primarily custom refiners, the four and eight largest mining firms are the same as the four and eight largest manufacturing firms.

3 The monopoly pricing model is identical to a collusive oligopoly model in which industry MR is equated to industry LRMC. In an oligopoly with a price leader, the leader's MR will be equated to its LRMC. In the latter case, the firm's demand (D) and MR curves will be more elastic than the industry's, but the figure will look very similar.

4 The long-run average cost function will shift downward with improvements in technology and upward with resource depletion, but its slope will be determined by deposit quality.

5 The assumption of no alternatives uses, while an oversimplification, is not totally unrealistic for a commodity like copper that is produced mainly in the arid Southwest. If land used for mining has alternative uses, such as in agriculture, then rent will be the price of land minus the transfer price (its price in the highest alternative use).

6 $\overline{Q}$ is actually calculated as

$$Q_o + \sum_{i=t_o}^{t-1} Q_i.$$

The summation extends only to t-1 so that $d\overline{Q}/dQ = 0$ and η is still the elasticity of total cost.

7 The conditions placed on TC thus far, together with the assumption of cost minimization, assure that there is a well-defined production function that is dual to TC [Shepherd 1970].

8 In some cases, v was found to be first-order serially correlated and a correction for this correlation was performed as noted in tables I and II.

9 In general, the instruments were: the exogenous variables in the equation plus Q_{-1}; P_{-1}; and U.S. copper imports, exports, and consumption, each lagged one year; U.S. manufacturing output; and world copper output.

10 Equation 11 could be estimated jointly with one cost-share equation (data on capital not being available). However, because the share equations are factor shares of total revenues, not total costs, they do not sum to one. The results shown in table I pertain to the single-equation estimates of the cost function, because, when the standard tests for positivity of the input-demand functions and convexity of the cost function were applied, the single-equation estimate was much better behaved than was the cost function obtained from the joint estimate.

11 The assumption of no change in w/r is similar to that made by Ricardo (i.e., a homogeneous dose of capital and labor is applied to nonhomogeneous land.) However, this assumption is not completely realistic. In general, copper industry wages have risen relative to capital costs over the last century. On the other hand, the fundamental changes in technology that made possible the switch from the underground mining of the native copper deposits of the Upper Peninsula of Michigan, which dominated production in the 19th century, to the strip mining of the porphyry deposits of the Southwest, which predominate today, should outweigh any changes in w/r.

12 Time is measured in years; 1800 = 0.

13 Data on the eight-firm concentration ratio are available only since 1911.

14 Between 1948 and 1974, the eight-firm concentration ratio for the non-communist-world copper industry fell from 77 to 28.

15 The LME price is determined in daily auctions and fluctuates with short-run changes in supply and demand.

16 The year 1954 was chosen as the dividing year because the London Metal Exchange was closed for 14 years prior to that time.

17 $\dot{X}/X_t$ is calculated as $(X_t - X_{t-1})/X_t$, where X = P or MC.

18 Equation 14 contains lagged endogenous variables and a serially correlated error term. Fair's [1970] method, which is consistent and asymptotically efficient, was used to estimate it.

19 The t-statistic to test the hypothesis that $a_3 + a_4 + a_5 = 0$ is -.49. Heal and Barrow also found that the coefficients of $\dot{MC}/MC$ (a_6, a_7, and a_8) summed to zero, a result not duplicated here.

20 In general the r's in the two equations will not be the same, the r in the cost function being the rental price of capital to the firm while that in the Heal-Barrow equation being the rate of return to assets of comparable risk to holding a mineral deposit. However, for empirical purposes, a measure of the opportunity cost of capital was used in both equations.

21 The expectation of $\eta \bar{-} 1$ (the estimated coefficient of Q from the mis-specified equation) is

$$E(\eta \bar{-} 1) = \eta - 1 + P_{\rho,Q}\beta_{\rho} = \eta - 1 + P_{\rho,Q}$$

where $\eta - 1$ is the regression coefficient from the properly specified equation ($P = MC + \rho$), $P_{\rho,Q}$ is the partial correlation coefficient between rent (ρ) and output (Q) and is β_{ρ} the regression coefficient of ρ in the properly specified equation. [See Johnston 1972 pages 168-169].

22 Deposit quality (and therefore production cost) is likely to vary even more in the world copper industry than in the U.S. industry because a larger variety of deposit types is involved.

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APPENDIX: DATA SOURCES

Copper price is an annual average of the U.S. producer price of refined copper compiled by the American Bureau of Metal Statistics and found in Non-Ferrous Metal Data.

Copper production is the annual output of U.S. copper smelters recorded by the U.S. Bureau of Mines and published in Minerals Yearbook.

Copper wages are production-worker average weekly earnings compiled by the U.S. Department of Labor, Bureau of Labor Statistics and found in Employment and Earnings.

Capital costs are always a problem. Several possible measures were experimented with—various interest rates (the cost of borrowing money), profitability measures (the opportunity cost of capital), and the manufacturing-capital rental price listed in Wills [1979]. (This last index is available only to 1974 and was, therefore, not used for the final estimates). The final choice for the equations listed in table I was the ratio of after-tax profits to stockholders' equity for all manufacturing corporations, compiled by the U.S. Federal Trade Commission and published in Quarterly Financial Report for Manufacturing Corporations. A different capital-cost variable was used in estimating equation 14. The rate on prime commercial paper, four to six months, found in Historical Statistics of the U.S. and in Statistical Abstracts of the U.S. 1978 was chosen because it is the longest consistent time series on interest rates available.

Labor productivity in copper mining (recoverable metal) is an index compiled by the Bureau of Labor Statistics and available from their Office of Productivity and Technology.

The average yield of copper ores mined in the United States is computed by the U.S. Bureau of Mines and published in Minerals Yearbook.

Concentration ratios in copper mining were computed by the author. Their construction is documented in Slade [1979].

Because the variables in all the equations are in natural logarithms, the units chosen needn't be consistent. For example, price is in cents per pound, output is in 10^3 short tons per year, and wages are in dollars per week.