Market Power in Nonrenewable Resource Markets: An Empirical Dynamic Model*

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Abstract

This paper estimates a dynamic model of the world markets for five nonrenewable resources over the period 1970-2004 and tests for market power in each of these markets. The results show that during the study period the world markets for copper, iron, lead, tin, and zinc were characterized by oligopolistic behavior. Our model enables us to estimate an upper bound for the price elasticity of demand for those markets exhibiting market power. We find that the demand for copper, iron, lead, and zinc is relatively inelastic, while the demand for tin is extremely elastic.

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I. Introduction

Nonrenewable resources are important resources in the modern economy. From fossil fuels to various minerals, nonrenewable resources are used to provide energy and input materials in numerous industries. Businesspeople, policy makers and researchers, especially economists, have paid much attention to the study of nonrenewable resource markets, including the demand and supply for these resources.

Nonrenewable resources share the characteristic that they cannot be replenished in a conceivable time horizon. Thus, persistent extraction will eventually lead to physical or economic depletion. With the expansion of the economy, it is reasonable to expect that the demand for nonrenewable resources might grow. However, this growth in demand may also be offset in part by technological advances in the efficiency of nonrenewable resource use. Technological progress may impact supply conditions as well, as technological progress in nonrenewable resource extraction may decrease the costs of extraction (Hotelling, 1931; Lin and Wagner, 2007).

The world markets for nonrenewable resources have undergone many changes since the 1970s. On the demand side, industrialized countries have experienced slower growth rates compared to the pre-1970 period and a gradual decline of the resource intensity of GDP. Meanwhile, the demand for nonrenewable resources of developing countries, especially those in East Asia, has been increasing. On the supply side, new technologies have expanded the resource reserves and have made extracting and refining lower grade resources profitable. Moreover, the rapid growth of demand before the 1970's left most of the countries that supply nonrenewable resources with excessive capacities in both mining and processing (Auty, 2000). Owing to the complex nature of world markets for nonrenewable resources since the 1970s, it is of interest to examine the world markets for nonrenewable resources in the post-1970 period.

The economics of nonrenewable resources was first examined by Hotelling (1931), who developed a theoretical model of optimal nonrenewable resource extraction, and who compared the market structures of perfect competition and monopoly. Salant (1976) and Ulph and Folie (1980) expanded Hotelling's (1931) seminal model of nonrenewable resource extraction to allow the market to consist of a cartel and a competitive fringe. Benchekroun, Halsema and Withagen (2009) give a full characterization of the open-loop Nash equilibrium of a nonrenewable resource game between two types of players differing in extraction costs. Extensive publications are devoted to the world oil market, especially OPEC and its strategies (see e.g., Hnyilicza and Pindyck, 1976; Cremer and Weitzman, 1976; Lin, 2009; Lin Lawell, 2016).

The empirical literature analyzing market power in the markets for nonrenewable resources other than oil has been relatively sparse to date. Ellis and Halvorsen (2002) estimate market power in the international nickel industry, and their results reject price-taking behavior. Cerda (2007) finds evidence of market power in the global copper market, but does not use a dynamic model. Haftendorn and Holz (2010) find that for the international market for steam coal, perfect competition better fits the observed real market flows and prices than does Cournot competition, but they do not use a dynamic model. As there have been few empirical studies to date analyzing market power in the markets for nonrenewable resources other than oil, and fewer still that use a dynamic model, whether or not there is market power in the world markets for non-energy nonrenewable resources is still an open question that has yet to be satisfactorily addressed.

To better understand the world markets for nonrenewable resources, this paper estimates a dynamic model of the world markets for five nonrenewable resources over the period 1970-2004 and tests for market power in each of these markets. Our model enables us to estimate an upper bound for the price elasticity of demand for those markets exhibiting market power.

The nonrenewable resources we have chosen to examine are copper, iron, lead, tin, and zinc. We choose these resources because unlike for oil and other fossil fuels, there have been few empirical studies to date analyzing market power in the markets for these five nonrenewable resources, and fewer still that use a dynamic model. We also choose these nonrenewable resources because they are important for the world economy, and are resources for which we are able to collect data on extraction, price and cost.

The research in this paper makes several contributions to the existing literature. First, it takes to data the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling (1931), and later expanded upon by many others to allow for features such as stock effects in extraction costs and technological progress.

A second contribution is that this paper develops a dynamic model that enables one to test for the market conduct of nonrenewable resource suppliers. We build upon the literature on conduct parameter analysis (see e.g., Genesove and Mullin, 1998; Corts, 1999; Clay and Troesken, 2003; Wolfram, 1999; Kim and Knittel, 2006) by estimating a dynamic model. As we explain below, the inclusion of the shadow price in the supply-side first-order condition is what makes our model dynamic as opposed to static. The dynamics in this paper therefore arise from the nonrenewable nature of the resource.[i]

A third contribution is that this paper builds upon existing empirical studies of nonrenewable resource markets by addressing the identification problem that arises in empirical analyses of supply and demand. Because the observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem (Angrist et al., 2000; Goldberger, 1991; Manski, 1995; Lin, 2011). A fourth contribution is that this paper estimates an upper bound for the price elasticity of demand for those markets exhibiting market power.

Our results show that during the study period the world markets for copper, iron, lead, tin, and zinc were characterized by oligopolistic behavior. We find that the demand for copper, iron, lead, and zinc is relatively inelastic, while the demand for tin is extremely elastic.

II. Model

We present a Hotelling model of nonrenewable resource extraction under the market structures of perfect competition and Cournot oligopoly. We expand upon Hotelling's (1931) basic model by allowing for Cournot oligopoly, and by deriving a general supply-side first-order condition that includes perfect competition and Cournot oligopoly as special cases, depending on the value of the conduct parameter. The notation follows that used by Weitzman (2003), Lin and Wagner (2007), Lin (2009), and Lin et al. (2009).

Let t index time. At time t, each producer j supplies $q_j(t)$ of the nonrenewable resource. The total quantity supplied at time t is given by $Q(t) = \sum_j q_j(t)$. The market price of a nonrenewable resource at time t is $P(t)$. The corresponding demand is given by $D(P(t))$. At each time t, the market price $P(t)$ adjusts to equate supply and demand:

$$Q(t) = D\big(P(t)\big) \ \forall t. \qquad (1)$$

$C(S, Q)$ depicts the cost of extracting Q tons of the resource when the stock of the resource remaining in the ground is S. Solow and Wan (1976) as well as Swierzbinski and Mendelsohn (1989) discuss procedures for aggregating across multiple deposits of an exhaustible resource with different extraction costs.

The term "stock effects" refers to the dependence of extraction cost on the stock S of reserve remaining in the ground. There are several possible reasons why this dependence is negative. First, extraction costs may increase as more of the stock is extracted (and less remains in the ground) if the resource needed to be extracted from greater depths as it was being depleted. Second, costs may increase if well pressure declined as more of the reserve was depleted. Third, since different grades of a resource may differ in their extraction costs, and since the cheaper grades are likely to be mined to exhaustion before the more expensive grades are mined, the cost of extraction may increase as the cheaper grades are exhausted.

Let $p(t)$ denote the non-negative current-value shadow price measuring the value of a ton of reserve in situ at time t. This shadow price is known by a variety of terms, including marginal user cost, in situ value, scarcity rent, dynamic rent, and resource rent (Devarajan and Fisher, 1982; Krautkraemer, 1998; Weitzman, 2003). The competitive interest rate is r.

The resource producer's optimal nonrenewable resource extraction problem is to choose the extraction profile $\{Q(t)\}$ to maximize the present discounted value of the entire stream of per-period net benefits $G(S, Q)$, given initial stock S_0 and the relationship between extraction $Q(t)$ and stock remaining $S(t)$, and subject to the constraints that both extraction and stock are nonnegative. The resource producer's problem is thus given by:

$$\max_{\{Q(t)\}} \int_0^\infty \Big(G\big(S(t), Q(t)\big)\Big) e^{-rt}\, dt$$

$$\begin{aligned} \text{s.t.} \quad & \dot{S}(t) = -Q(t) \qquad : p(t) \\ & Q(t) \geq 0 \\ & S(t) \geq 0 \\ & S(0) = S_0 , \end{aligned} \tag{2}$$

where the co-state variable $p(t)$ associated with the remaining stock $S(t)$ is the shadow price $p(t)$ of the reserve still in the ground, measuring the marginal value in terms of present discounted net benefits that could be obtained with an extra unit of reserve.

Under perfect competition, the per-period net benefits $G(S, Q, t)$ from extracting Q tons at time t are given by total benefits $U(Q, t)$ minus total costs:

$$G(S, Q) = U(Q) - C(S, Q). \tag{3}$$

Assuming that the social and private discount rates are the same, that the initial stock S_0 is known, and that there are no externalities, the social planner's optimal control problem yields the same solution as would arise in perfect competition.[ii] In this case, under the additional assumption that the marginal utility of income is constant, the total benefits $U(Q)$ that accrue from the consumption of the resource at time t are given by the area under the demand curve:

$$U(Q(t)) = \int_0^{Q(t)} D^{-1}(x)dx, \tag{4}$$

where $D^{-1}(\cdot)$ is the inverse of the demand curve with respect to price. This area measures the gross consumer surplus, and is a measure of the consumers' willingness-to-pay for the resource. Weitzman (2003) shows that using the area under the demand curve in place of revenue yields the same outcome as a perfectly competitive market. Thus, in the absence of externalities, a perfectly competitive market maximizes total utility, or what Hotelling (1931) terms the "social value of the resource".

When the nonrenewable resource is produced by a group of Cournot oligopolists, rather than by a multitude of perfectly competitive producers, the per-period net benefits $G(S, Q)$ are given by the per-period profit of oligopolists, which for each producer j is j's revenue $R_j(q_j)$ minus its costs $C_j(S_j, q_j)$. The revenue $R_j(\cdot)$ is given by:

$$R_j(q_j(t)) = D^{-1}(Q(t)) \cdot q_j(t), \tag{5}$$

and the per-period net benefits is given by:

$$G_j(S, q_j) = R_j(q_j) - C_j(S_j, q_j). \tag{6}$$

From the Maximum Principle, one first-order necessary condition for a feasible trajectory $\{S^*(t), Q^*(t)\}$ to be optimal under perfect competition is:

$$\text{[\#1 perfect competition]:} \qquad P(t) = \frac{\partial C(\cdot)}{\partial Q} + p(t). \tag{7}$$

Under Cournot oligopoly, this first-order condition is:

$$\text{[\#1 Cournot]:} \qquad P(t) = -\frac{dD^{-1}(Q(t))}{dQ} q_j(t) + \frac{\partial C_j(\cdot)}{\partial q_j} + p_j(t). \tag{8}$$

A second first-order condition governs the time rate of change of the shadow price:

$$\text{[\#2]:} \quad \dot{p}(t) = \frac{\partial C(\cdot)}{\partial S} + rp(t), \tag{9}$$

which, in the absence of stock effects ($\frac{\partial C(\cdot)}{\partial S} = 0$), yields the Hotelling rule that the shadow price rises at the rate of interest:

$$p(t) = p(0)e^{rt}. \tag{10}$$

If we allow for the possibility that producers behave either as Cournot oligopolists or perfectly competitive price-takers, the general supply-side first-order condition is:

$$P(t) = -\theta_1 \frac{dD^{-1}(Q(t))}{dQ} q_j(t) + \frac{\partial C_j(\cdot)}{\partial q_j} + p_j(t), \tag{11}$$

where θ_1 is the conduct parameter. If $\theta_1 = 0$, then the producers of the nonrenewable resource are perfectly competitive price takers; if $\theta_1 = 1$, then the producers are Cournot oligopolists. If $\theta_1 \in (0,1)$, this means that the producers exert an intermediate degree of market power.

III. Data

We use annual country-level data on extraction, price and cost of five nonrenewable resources over the period 1970 to 2004 from the World Bank.[iii] These nonrenewable resources are copper, iron, lead, tin, and zinc. Table 1 presents the summary statistics for our data.

The use of annual data is appropriate for our analysis because it enables us to focus on analyzing market power in a parsimonious model, without having to control for the many short-term phenomena and factors such as weather shocks and daily or monthly economic fluctuations that may lead to variations in market prices in higher frequency data. In particular, as we show in our empirical model below, annual data on price, extraction, and cost, along with country fixed effects, enables us to best measure market power using the general supply-side first-order condition (11).

Since the only cost data available are data on average costs, not marginal costs, with respect to extraction, we use average costs as a proxy for marginal costs in estimating the supply-side first-order condition. There are several reasons why average cost may serve as a proxy for marginal costs. First, in his empirical model of the shadow price for 14 nonrenewable resources, Atewamba (2011, 2013) finds that he cannot reject that marginal extraction cost is equal to average extraction cost at a 5% level for copper, iron, lead, tin, and zinc. He concludes that it should therefore be acceptable to use the average extraction cost data as a proxy for marginal extraction cost. Atewamba (2011, 2013) uses the same data for average extraction cost that is used in this paper.

A second reason that average costs may be an acceptable proxy to use for marginal costs is that the assumption of constant returns to scale in the extraction of nonrenewable resources is commonly made in the literature on nonrenewable resources. Average costs would equal marginal costs if extraction costs exhibit constant returns to scale with respect to extraction. It is often posited that the extraction cost function exhibits constant returns to scale, where the marginal extraction cost is increasing in cumulative extraction but independent of the current rate of extraction, and therefore that average cost and marginal cost are the same (see e.g., Solow and Wan, 1976; Hanson, 1980; Lin and Wagner, 2007).

A third reason that average costs may be an acceptable proxy to use for marginal costs is that the assumption of constant returns to scale enables one to define an aggregate extraction cost function that aggregates across multiple deposits of an exhaustible resource with different extraction costs. Solow and Wan (1976) and Swierzbinski and Mendelsohn (1989) show that in the absence of exploration, if firms extract first from the cheapest deposits and there are constant returns to scale in extraction, then an aggregate extraction cost function can be defined and indexed by the amount of cumulative extraction.

To control for any time-invariant country-specific differences between average costs and marginal costs as well as any time invariant country-specific stock effects that would cause the shadow price to evolve differently from the rate of interest, we include country fixed effects in the empirical estimation.

Before conducting the empirical analysis, we provide descriptive statistics measuring market power. Table 2 summarizes the number of supplying countries of each mineral each year during the study period. Minerals markets with a smaller number of suppliers are more likely to exhibit market power, since they have fewer suppliers. There are variations among the nonrenewable resources and from year to year. Tin has fewest suppliers and iron has most suppliers on average. Among the five nonrenewable resources, tin went through the least change in the number of suppliers.

Table 3 summarizes the Herfindahl-Hirschman Index (HHI), calculated using percents as whole numbers, of the market of each mineral in each year. The markets for minerals with higher HHI are more likely to exhibit market power. The United States Department of Justice uses 1800 points of HHI as a threshold: markets whose HHI is above 1800 are considered to be concentrated. During the study period, none of the markets have an average HHI greater than 1800 points. However, for tin, the maximum HHI over all the years is greater than 1800 points, which means that the market for tin was considered to be concentrated for at least 1 year during the period of study.

IV. Empirical Estimation

The econometric model allows for the possibility that producers behave either as Cournot oligopolists or perfectly competitive price-takers. We estimate the following empirical specification of the general supply-side first-order condition (11) from our theory model for each of the five nonrenewable resources:

$$P_t = -\tilde{\theta}_1 q_{jt} + \beta AC_{jt} + p_{j0} e^{rt} + \alpha_j + \nu_{jt}, \qquad (12)$$

where P_t is the real price of the mineral in year *t*, q_{jt} is the quantity extracted of the mineral in country *j* in year *t*, AC_{jt} is the average cost for that mineral in country *j* in year *t*, α_j is a country fixed effect, ν_{jt} is an error term, $\theta = (\tilde{\theta}_1, \beta, p_{j0})$ are the parameters to be estimated, and $\tilde{\theta}_1$ is the following function of the conduct parameter θ_1 and the inverse world demand:

$$\tilde{\theta}_1 = -\theta_1 \frac{dD^{-1}(Q(t))}{dQ}. \qquad (13)$$

To estimate equation (12), we run a two-stage least squares regression of the world price of the nonrenewable resource on the quantity supplied by each country, the average cost for each supplying country, country fixed effects, and country fixed effects interacted with e^{rt}. We incorporate the shadow price into the regression by including as a regressor a country fixed effect interacted with e^{rt}, so that the coefficient p_{j0} on this regressor is the country-specific initial shadow price in 1970 under the assumption that there are no stock effects. We set the discount rate r to 5% for the base case scenario, and vary the value of r between 3% and 6% in alternative scenarios. These values of the discount rate represent a reasonable range of possible values for the discount rate given historical world real interest rates during the time period of our data set (OECD, 2016; World Bank, 2016). The country fixed effect α_j absorbs any time-invariant country-specific differences between average costs and marginal costs as well as any time invariant country-specific stock effects that would cause the shadow price to evolve differently from the rate of interest.[iv] So that the standard errors are robust to the presence of arbitrary heteroskedasticity, we calculate robust standard errors using a Eicker-Huber-White-sandwich estimator of variance.

The inclusion of the shadow price in the supply-side first-order condition is what makes the model dynamic as opposed to static. While a statically optimizing producer would satisfy price equals marginal cost plus markup, a dynamically optimizing producer would also incorporate the shadow price, which measures the foregone future net benefits from extracting the resource from the ground today rather than leaving it in the ground for later, and therefore would satisfy price equals marginal cost plus markup plus the shadow price. The dynamics in this paper therefore arise from the nonrenewable nature of the resource.

Because the observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, quantity is endogenous in the supply equation (12) given by the supply-side first-order condition, and therefore must be instrumented. We use the following variables as instruments for the nonrenewable resource quantity extracted q_{jt} in country *j* in year *t*: the population of country *j* in year *t*, the GDP of country *j* in year *t*, world population in year *t*, and world GDP in year *t*. Population and income are demand shifters that are correlated with quantity but do not affect price except through their effect on quantity, and thus serve as good instruments for quantity in the supply equation. Both country-level and global shifters of demand serve as good instruments for quantity in the supply equation as we are analyzing the world market for these nonrenewable resources. For each mineral, we use as instruments only the variables from among the four candidate instruments that are significant in the first-stage regression.[v]

To examine the importance of instrumenting for quantity, we test whether quantity is endogenous in our regression model (12). Under the null hypothesis that quantity can actually be treated as exogenous, the test statistic in our endogeneity test is distributed as chi-squared with 1 degree of freedom. The test statistic is based on the difference of two Sargan-Hansen statistics: one for the equation with the smaller set of instruments, where quantity is treated as endogenous, and one for the equation with the larger set of instruments, where quantity is treated as exogenous. Under conditional homoskedasticity, this endogeneity test statistic is numerically equal to a Hausman test statistic (Hayashi, 2000; Baum, Schaffer and Stillman, 2007). Unlike Durbin-Wu-Hausman tests, the test statistics we use are robust to various violations of conditional homoscedasticity (Baum, Schaffer and Stillman, 2007).

According to the results of our endogeneity test (which are also reported in Table 5), the p-values for quantity extracted are greater than 0.05 for lead (p-value = 0.150) and zinc (p-value = 0.482), so we do not reject the null hypothesis that quantity is exogenous for these minerals. However, we reject the null hypothesis that quantity is exogenous at a 0.1% level for copper (p-value = 0.000), iron (p-value = 0.000), and tin (p-value = 0.000). Since we reject the null hypothesis that quantity extracted is exogenous for copper, iron, and tin, and since owing to simultaneity it is likely that quantity is endogenous for lead and zinc as well, we instrument for quantity in estimating the supply-side first-order condition (12).

Table 4 presents the results from the first-stage regressions. The first-stage Kleibergen-Paap F-statistics are all either close to or greater than 10. As seen in Table 5, the instruments pass the Anderson underidentification test, rejecting the null hypothesis of underidentification. In addition, the instruments pass weak-instrument-robust inference tests as well, rejecting the null hypothesis that the coefficients on the endogenous regressors in the structural equation are jointly equal to zero, and thus alleviating any concerns regarding weak instruments (Stock and Yogo, 2005).

The coefficient on quantity is given by equation (13), which is a product of the market conduct parameter θ_1 and the (absolute value of the) slope of the inverse demand curve. If the coefficient on the quantity of a nonrenewable resource supplied by each country is statistically significant, then, assuming that the slope of the inverse demand curve is non-zero, this means that $\theta_1 > 0$ and therefore that the suppliers of the resource exert market power as (possibly imperfect) Cournot oligopolists; otherwise, $\theta_1 = 0$ and the suppliers behave as price-takers. With an assumption that demand is downward-sloping, we expect the coefficients on quantity to be positive when $\theta_1 > 0$.

Table 5 presents the results from estimating the model. For all five minerals, the coefficients on quantity extracted are statistically significant, which means that the suppliers of these minerals behaved oligopolistically. Moreover, the coefficients are positive, which is consistent with a downward-sloping demand function. Across all minerals, as expected, average costs have significantly positive effects on prices.

For each of the five minerals, to test whether a dynamic model is appropriate for the world market for that mineral, we test the significance of the shadow price for that mineral by testing the joint significance of the coefficients p_{j0} on the country fixed effects interacted with e^{rt} for that mineral. The shadow prices are jointly significant for iron and tin, which confirms that a dynamic model that incorporates the shadow price is the appropriate model for the world markets for these two minerals.

Table 6 presents results allowing conduct parameters and elasticities to vary by time period. In particular, we allow the coefficient on quantity in the years 1970-1989 to vary from the coefficient on quantity in the years 1990-2004. When the conduct parameters and elasticities are allowed to vary by time period, the coefficients on quantity are significant for copper, lead, tin, and zinc, but not for iron. The shadow prices are jointly significant for iron, lead and tin, which confirms that a dynamic model that incorporates the shadow price is the appropriate model for the world markets for these three minerals.

From equation (13), our model enables us to estimate an upper bound for the price elasticity of demand for those markets exhibiting market power. Table 7 presents the price elasticity of demand implied by our results from Tables 5 and 6 assuming that the producers behave as Cournot oligopolists ($\theta_1 = 1$) and evaluated at the respective mean price and quantity. If the producers behave as imperfect Cournot oligopolists ($\theta_1 \in (0,1)$), then the reported magnitudes are upper bounds. We find that the demand for copper, iron, lead, and zinc is relatively inelastic, while the demand for tin is extremely elastic.

Table 8 presents the results from estimating the model using different discount rates *r* between 3% and 6%. For the most part, the signs and significances of the conduct parameters are robust to the discount rate used. The magnitudes are fairly robust as well, and the confidence intervals generally overlap across the different discount rates. The shadow prices are jointly significant for at least one discount rate for copper, iron, lead, and tin, which provides evidence that a dynamic model that incorporates the shadow price is the appropriate model for the world markets for these four minerals. Moreover, the shadow prices are jointly significant for all interest rates for iron and tin, which provides strong evidence that a dynamic model is the appropriate model for the world markets for these two minerals.

V. Conclusion

This paper estimates a dynamic model of the world markets for five nonrenewable resources over the period 1970-2004 and tests for market power in each of these markets. Our model enables us to estimate an upper bound for the price elasticity of demand for those markets exhibiting market power.

The research in this paper makes several important contributions to the existing literature. First, it takes to data the Hotelling model of optimal nonrenewable resource extraction. A second contribution is that this paper develops a dynamic model that enables one to test for the market conduct of nonrenewable resource producers. A third contribution is that this paper builds upon existing empirical studies of nonrenewable resource markets by addressing the identification problem that arises in empirical analyses of supply and demand. A fourth contribution is that this paper estimates an upper bound for the price elasticity of demand for those markets exhibiting market power.

The results from our dynamic model show that during the study period the world markets for copper, iron, lead, tin, and zinc were characterized by oligopolistic behavior. In contrast, a simple static analysis of market power using the Herfindahl-Hirschman Index (HHI), calculated using percents as whole numbers, shows that during the study period none of the markets have an average HHI greater than 1800 points, the threshold above which the United States Department of Justice considers a market to be concentrated.

Although the average HHI for these world minerals markets are low, the results of our dynamic model show that producers are able to influence the world price of these minerals through their choice of quantity, and therefore that these producers behave oligopolistically. A simple static analysis of market power using the Herfindahl-Hirschman Index that ignores the dynamics of nonrenewable resource markets arising from the nonrenewable nature of the resource and that ignores whether producers influence the world price through their choice of quantity may generate a misleading characterization of market power in world markets for nonrenewable resources. It is therefore important to use a dynamic model to test market conduct in order to assess market power in nonrenewable resource markets.

Our model also enables us to estimate an upper bound for the price elasticity of demand for those markets exhibiting market power. We find that the demand for copper, iron, lead, and zinc is relatively inelastic, while the demand for tin is extremely elastic.

The elastic demand for tin is likely due to the many substitutes available for tin. Much tin is used to coat tin cans, but plastics, paper, aluminum and glass can be used in place of metal tin cans. On balance, world consumption of tin has not grown during the past 20 years, due mainly to the substitution of tin by plastic in the manufacture of cans and other containers, such as tubes for toothpaste and ointments (Minerals Education Coalition, 2013).

Our research has several important implications. First, the results from our dynamic model, which differ from those of a simple static analysis of market power using the Herfindahl-Hirschman Index, demonstrate the importance of using a dynamic model to test market conduct in order to assess market power in nonrenewable resource markets. Second, our finding that the world markets for copper, iron, lead, and zinc exhibit inelastic demand and market power, combined with the nonrenewable nature of these resources, suggests that it may be important to find substitutes for copper, iron, lead, and zinc.

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Table 1. Summary Statistics

	Copper	Iron	Lead	Tin	Zinc
quantity extracted (thousand metric tons)					
Mean	141.451	8031.744	58.416	6.246	123.203
Std. Dev.	388.889	22173.05	123.611	13.722	256.519
Min	0	0	0	0	0
Max	5380	149000	950	100	2000
average cost of extraction (1982-1984 US $ per ton)					
Mean	1016	17.148	432.366	9496.576	724.823
Std. Dev.	361.471	7.495	109.772	5682.655	200.508
Min	150.008	4.352	220.583	2248.001	361.784
Max	2670.081	48.632	832.117	20839.45	1180.445
world price (1982-1984 US $ per ton)					
Mean	1910.503	38.17	651.551	8718.103	925.655
Std. Dev.	759.964	11.077	285.671	5733.535	332.113
Min	893.047	23.968	357.632	2248.557	452.807
Max	3797.831	63.954	1627.839	20840.82	2060.367

Table 2. Number of supplying countries each year

	Mean	Std. Dev.	Min	Max
Copper	66.10	8.82	49	77
Iron	68.07	11.13	45	74
Lead	55.90	7.82	42	67
Tin	35.52	5.43	24	40
Zinc	56.55	8.03	43	68

Table 3. Herfindahl-Hirschman Index by year

	Mean	Std. Dev.	Min	Max
Copper	1108.33	246.30	824.14	1695.34
Iron	1240.15	117.94	1053.26	1501.84
Lead	993.42	238.29	781.06	1714.02
Tin	1566.17	420.63	1012.50	2554.25
Zinc	908.15	86.36	795.36	1128.98

Note: The Herfindahl-Hirschman Index (HHI) is calculated using percents as whole numbers.

Table 4. First-stage regressions

	Dependent variable is quantity extracted (million metric tons) of:				
	Copper	Iron	Lead	Tin	Zinc
country GDP (trillion 1982-1984 US $)			-0.078***	0.023*	-0.168***
			(0.022)	(0.008)	(0.055)
world GDP (trillion 1982-1984 US $)	0.003***	0.426***	0.000		
	(0.001)	(0.088)	(0.001)		
country population (billion)	0.000*		0.000***		
	(0.000)		(0.000)		
world population (billion)		3.817 ***		-0.006**	
		(1.072)		(0.002)	
average cost of extraction (1982-1984 US $ per ton)	-0.026*	0.255	0.000	0.000**	0.000
	(0.011)	(0.258)	(0.000)	(0.000)	(0.000)
country fixed effects	Yes	Yes	Yes	Yes	Yes
country fixed effects * e^{rt}	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap first-stage F-statistic	5.105	12.716	8.696	10.758	9.278
# observations	1248	1576	1131	630	1145

Notes: Robust standard errors are in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 5. IV Results

	Dependent variable is world price (1982-1984 US $ per ton) of:				
	Copper	Iron	Lead	Tin	Zinc
quantity extracted (million metric tons)	68378.23**	0.646*	2612.94*	280.550***	1190.84*
	(23515.46)	(0.296)	(1177.10)	(62.936)	(605.29)
average cost of extraction (1982-1984 US $ per ton)	1.115*	2.061***	1.314***	1.000***	1.227***
	(0.523)	(0.260)	(0.045)	(0.000)	(0.036)
country fixed effects	Yes	Yes	Yes	Yes	Yes
country fixed effects * e^{rt}	Yes	Yes	Yes	Yes	Yes
p-value of joint significance of country fixed effects * e^{rt}	[0.205]	[0.000]***	[0.056]	[0.000] ***	[0.058]
p-value of test of endogeneity of quantity extracted	[0.000]***	[0.000]***	[0.150]	[0.000]***	[0.482]
Kleibergen-Paap first-stage F statistic	5.105	12.716	8.696	10.758	9.278
p-value of Anderson underidentification test	[0.005]**	[0.000]***	[0.000]***	[0.000]***	[0.003]**
Weak-instrument-robust-inference tests					
p-value of Anderson-Rubin F test	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.035]*
p-value of Anderson-Rubin Chi-sq test	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.027]*
p-value of Stock-Wright S statistic test	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.028]*
# observations	1248	1576	1131	630	1145

Notes: Robust standard errors are in parentheses. We use the following variables as instruments for quantity extracted q_{jt} in country *j* in year *t*: the population country *j* in year *t*, the GDP of country *j* in year *t*, world population in year *t*, and world GDP in year *t*. For each mineral, we use as instruments only the variables from among the four candidate instruments that are significant in the first-stage regression; the instruments used for each regression are presented in the first-stage regressions in Table 4. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 6. IV Results allowing conduct parameters and elasticities to vary by time period

	Dependent variable is world price (1982-1984 US $ per ton) of:				
	Copper	Iron	Lead	Tin	Zinc
quantity extracted (million metric tons)					
1970-1989	32179.12***	0.526	4001.208***	271.76***	1184.59***
	(8684.13)	(0.380)	(1068.42)	(60.63)	(562.38)
1990-2004	33966.96***	0.568	2436.76*	318.87***	920.69*
	(8224.34)	(0.328)	(1086.97)	(66.66)	(437.10)
average cost of extraction (1982-1984 US $ per ton)	1.230 ***	2.100***	1.356***	1.000***	1.225***
	(0.261)	(0.265)	(0.052)	(0.000)	(0.035)
country fixed effects	Yes	Yes	Yes	Yes	Yes
country fixed effects * e^{rt}	Yes	Yes	Yes	Yes	Yes
p-value of joint significance of country fixed effects * e^{rt}	[0.559]	[0.000]***	[0.000]***	[0.000] ***	[0.063]
# observations	1248	1576	1131	630	1145

Notes: Robust standard errors are in parentheses. We use the following variables as instruments for quantity extracted q_{jt} in country *j* in year *t*: the population country *j* in year *t*, the GDP of country *j* in year *t*, world population in year *t*, and world GDP in year *t*. For each mineral, we use as instruments only the variables from among the four candidate instruments that are significant in the first-stage regression; the instruments used for each regression are presented in the first-stage regressions in Table 4. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 7. Estimated price elasticities of demand

	Price Elasticity of Demand		
	Entire time period	1970-1989	1990-2004
Copper	-0.003 **	-0.009 ***	-0.004 ***
	(0.001)	(0.003)	(0.001)
Iron	-0.108 *	-0.177	-0.081
	(0.050)	(0.128)	(0.047)
Lead	-0.076 *	-0.057 ***	-0.063 *
	(0.034)	(0.015)	(0.028)
Tin	-141.25 ***	-207.71 ***	-48.62 ***
	(31.69)	(46.34)	(10.15)
Zinc	-0.112 *	-0.143 *	-0.100 *
	(0.057)	(0.068)	(0.047)

Notes: Robust standard errors are in parentheses. The calculations are made assuming that the producers behave as Cournot oligopolists. If the producers behave as imperfect Cournot oligopolists, then the reported magnitudes are upper bounds. The elasticities are evaluated at the respective mean price and quantity. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 8. IV Results for different discount rates

Dependent variable is world price (1982-1984 US $ per ton)	$r = 3\%$	$r = 4\%$	$r = 5\%$	$r = 6\%$
Copper				
quantity extracted (million metric tons)	32785.15***	48342.85**	68378.23**	60361.40**
	(9012.35)	(15035.84)	(23515.46)	(20149.98)
p-value of joint significance of country fixed effects * e^{rt}	[0.919]	[0.004]**	[0.205]	[0.129]
Iron				
quantity extracted (million metric tons)	2.117***	1.634***	0.646*	-0.342
	(0.486)	(0.415)	(0.296)	(0.267)
p-value of joint significance of country fixed effects * e^{rt}	[0.000]***	[0.000]***	[0.000]***	[0.000] ***
Lead				
quantity extracted (million metric tons)	25094.01*	10859.90*	2612.94*	1603.10*
	(11634.11)	(4560.81)	(1177.10)	(798.59)
p-value of joint significance of country fixed effects * e^{rt}	[0.801]	[0.109]	[0.056]	[0.000]***
Tin				
quantity extracted (million metric tons)	293.55***	284.38***	280.550***	282.81***
	(79.61)	(67.86)	(62.936)	(62.48)
p-value of joint significance of country fixed effects * e^{rt}	[0.000]***	[0.000]***	[0.000]***	[0.000]***
Zinc				
quantity extracted (million metric tons)	-620.86	1202.68	1190.83*	1258.28*
	(6209.20)	(943.51)	(605.29)	(541.40)
p-value of joint significance of country fixed effects * e^{rt}	[0.258]	[0.056]	[0.058]	[0.071]

Notes: Robust standard errors are in parentheses. Regressions include average cost of extraction, country fixed effects, and country fixed effects interacted with e^{rt}. We use the following variables as instruments for quantity extracted q_{jt} in country *j* in year *t*: the population country *j* in year *t*, the GDP of country *j* in year *t*, world population in year *t*, and world GDP in year *t*. For each mineral, we use as instruments only the variables from among the four candidate instruments that are significant in the first-stage regression; the instruments used for each regression are presented in the first-stage regressions in Table 4. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

[i] Corts (1999) shows that the conduct parameter can be inconsistently estimated if producers are engaging in efficient tacit collusion resulting from dynamic cartel behavior; however, Puller (2009) shows that in the first-order condition the extra term that results from a binding incentive compatibility constraint can be conditioned out using time fixed effects, yielding consistent estimates of the conduct parameter. We assume that there are no additional dynamics arising from efficient tacit collusion and therefore no need for the time fixed effects suggested by Puller (2009). We are unable to add year fixed effects because the dependent variable, the annual real world price, takes on only one value each year.

[ii] Even if social and private discount rates are not the same, if one uses the private discount rate instead of the social discount rate in the social planner's problem, one will obtain the same solution as would arise in perfect competition.

[iii] The analysis does not extend beyond 2004 due to data availability constraints. We thank Kirk Hamilton for providing the data. The World Bank data include average "rent" figures, which were calculated as extraction multiplied by the difference between price and average cost. Solving for average costs using this formula, we calculate average cost as price minus "unit rent", where "unit rent" is the "rent" provided in the data set divided by extraction.

[iv] We assume that there are no additional dynamics arising from efficient tacit collusion and therefore no need for the time fixed effects suggested by Puller (2009). We are unable to add year fixed effects because the dependent variable, the annual real world price, takes on only one value each year.

[v] Although world GDP is not significant in the first-stage regression for lead, we include it as an instrument in the lead regressions because doing so increases the Kleibergen-Paap first-stage F-statistic.