Market Power in the World Oil Market:

Evidence for an OPEC Cartel and an Oligopolistic Non-OPEC Fringe

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Abstract

This paper estimates a Hotelling model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved oligopolistically over the period 1970-2004. Results of the analysis by decade support OPEC countries colluding as the dominant cartel producer and non-OPEC countries behaving as an oligopolistic fringe. Market demand has become more inelastic over time over the period of study. The estimated shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is.

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1 Introduction

Economists have long been interested in OPEC and the world oil market. The mission of OPEC is to 'coordinate and unify the petroleum policies of its Member Countries' (OPEC, 2017). Nevertheless, it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016; Baumeister and Kilian, 2017).

As a step towards better understanding and modeling the world oil market and OPEC in particular, this paper estimates a Hotelling model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004.

The Hotelling model developed and estimated in this paper accounts for the nonrenewable nature of the resource; addresses the identification problem that arises in empirical analyses of supply and demand; and enables one to test for the market conduct of OPEC and non-OPEC producers. We allow for the possibility that market structure and demand elasticities may have changed over time during this time period.

Results of the analysis by decade support OPEC countries colluding as the dominant cartel producer and non-OPEC countries behaving as an oligopolistic fringe. Market demand has become more inelastic over time over the period of study. The estimated shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is.

The balance of this paper proceeds as follows. Section 2 situates this paper in the previous literature. Section 3 presents the theoretical Hotelling model of nonrenewable resource extraction under the market structures of perfect competition, Cournot oligopoly, monopoly (or collusion), and an OPEC cartel with a non-OPEC fringe. Section 4 presents the data. Section 5 presents the empirical estimation. Section 6 concludes.

2 Previous Literature

The research in this paper builds on several strands of existing literature.

First, we take 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 such features as Nash-Cournot behavior (Salant, 1976; Ulph and Folie, 1980); OPEC (Hnyilicza and Pindyck, 1976; Pindyck, 1976; Crémer and Weitzman, 1976); strategic behavior (van Veldhuizen and Sonnemans, 2018); stock effects in extraction costs (Solow and Wan, 1976; Hanson, 1980; Farzin, 1992); exploration (Pindyck, 1978; Pesaran, 1990); market imperfections (Stiglitz, 1976; Khalatbari, 1977; Sweeney, 1977; Crémer and Salehi-Isfahani, 1991); technological progress (Farzin, 1992, 1995; Lin et al., 2009; Lin and Wagner, 2007; Meier and Quaas, 2020); outward-shifting demand (Chapman, 1993; Chapman and Khanna, 2000); uncertainty (Hoel, 1978; Pindyck, 1980); risk (Young and Ryan, 1996); drilling activity (Anderson, Kellogg and Salant, 2018); stochastic and volatile output price and production cost (Almansour and Insley, 2016); tax policy (Leighty and Lin, 2012); market power (Zhang and Lin Lawell, 2017); and oil contracts (Ghandi and Lin, 2012; Ghandi and Lin Lawell, 2020).

Gaudet (2007) provides a recent review of factors that can potentially help bridge the gap between the basic Hotelling rule of natural resource exploitation and the historical behavior of the flow price of a number of resources. Lin (2009) shows that even the most basic Hotelling model yields insights.

Unlike many previous empirical studies of the petroleum market, which use a static model, this paper estimates a Hotelling model of the world petroleum market, which is a dynamic model. Crémer and Salehi-Isfahani (1991) provide a survey of models of the oil market. Livernois (2009) and Slade and Thille (2009) present thorough reviews of the empirical literature on the Hotelling model.

A second contribution is that this paper builds upon existing empirical studies of nonrenewable resource markets (see e.g., Adelman, 1962; Berndt and Wood, 1975; Gately, 1984; Gately and Huntington, 2002; Griffin, 1985; Hausman, 1975; Kennedy, 1974; Nordhaus, 1980;

Young, 1992) 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 (Goldberger, 1991; Manski, 1995; Angrist et al., 2000; Lin, 2011).

The third contribution is that this paper develops a Hotelling model that enables one to test for the market conduct of OPEC and non-OPEC producers. This paper builds upon the work of Griffin (1985), who tests alternative models of OPEC behavior using quarterly data over the period 1971-1983, by using a dynamic model, by using instrumental variables to address endogeneity, and by incorporating two additional decades of recent data. It expands upon the work of Matutes (1988) by using instruments and by incorporating more recent data. It builds on Golombek, Irarrazabal and Ma's (2018) empirical dominant firm model of the oil market of by estimating a dynamic model. It also expands on the work of Gülen (1996), who uses cointegration and causality tests to test implications of OPEC cartel behavior. Farzin (1985) estimates a supply function for non-OPEC producers using U.S. data from 1973-1978; this paper considers the supply function for both OPEC and non-OPEC producers over a longer period of time. Smith (2005) applies a production-based approach for examining alternative hypotheses, and finds strong evidence of cooperative behavior among OPEC members.

OPEC behavior is also analyzed by Alhajji and Huettner (2000a,b), Kaufmann et al. (2004), Almoguera, Douglas and Herrera (2011), Hochman and Zilberman (2015), Ratti and Vespignani (2015), Okullo and Reynès (2016), Genc (2017), Ghoddusi, Nili and Rastad (2017), Benchekroun, van der Meijden and Withagen (2017), Klein (2018), Al Rousan, Sbia and Onur Taş (2018), Plante (2019), Parnes (2019), Asker, Collard-Wexler and De Loecker (2019), and Branger, Flacke and Gräber (2020). For a detailed review of the literature on oil market modeling and OPEC's behavior, see Al-Qahtani, Balistreri and Dahl (2008).

This paper also builds upon the literature on conduct parameter analysis (see e.g., Sullivan, 1985; Genesove and Mullin, 1998; Corts, 1999; Clay and Troesken, 2003; Wolfram, 1999; Kim and Knittel, 2006) by embedding a conduct parameter analysis in a Hotelling model, which is a dynamic model, rather than using a static model as is traditionally done with conduct parameter analysis. As explained below, the inclusion of the shadow price in the supply-side first-order condition is what makes the model in this paper dynamic as opposed to static. The dynamics in this paper therefore arise from the nonrenewable nature of the resource.[2]

3 Hotelling Model Under Different Market Structures

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

Let t index time. We assume that each time period is a year, in order to smooth over daily or monthly shocks to supply or demand. While production may be capacity constrained at a monthly level until more wells are drilled (Anderson, Kellogg and Salant, 2018), production is less likely to be constrained at an annual level since during the period of the data set it took about 3 months (i.e., much less than a year) to initiate and complete a drilling program (Hendricks and Porter, 1996). As a consequence, producers are likely able to respond at an annual level to any capacity constraints they might face at a monthly level by drilling more wells. Moreover, OPEC spare capacity, which the Energy Information Administration defines as the volume of production that can be brought on within 30 days and sustained for at least

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[2] 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). I am unable to add year fixed effects because the dependent variable, the annual real world oil price, takes on only one value each year.

90 days (EIA, 2016b), has been high for most of the period of the data set, and was around 10 million barrels per day in 1985 (Fattouh, 2006), suggesting that capacity constraints may have been less of an issue at an annual level during the period analyzed in this paper.[3] Thus, we model each time period as a year,

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 oil 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:

$$Q(t) = D(P(t)) \; \forall t. \tag{1}$$

The cost function $C(S, Q)$ depicts the total cost of extracting Q tons when the stock of oil 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. As discussed in detail below, we assume constant returns to scale in extraction, which 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.

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 of oil reserve 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

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[3] OPEC spare capacity was low in 2005 and 2006 (EIA, 2016b), but this occurred after the period of the data set, which spans 1970-2004.

reserve was depleted. Third, since different grades of oil may differ in their extraction costs, and since production may move towards more expensive grades as the stock of cheaper grades diminishes, the cost of extraction may increase as the stock of cheaper grades and therefore the total stock decreases.

Let $\mu(t)$ 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 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_o and the relationship between extraction $Q(t)$ and stock remaining $S(t)$, and subject to the constraints that both extraction and stock are non-negative. The producer's problem is thus given by:

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\begin{aligned}
&\max_{\{Q(t)\}} \int_0^\infty \left(G(S(t), Q(t))\right) e^{-rt} dt \\
&\text{s.t.} \qquad \dot{S}(t) = -Q(t) \qquad : \mu(t) \\
&\qquad\qquad Q(t) \geq 0 \\
&\qquad\qquad S(t) \geq 0 \\
&\qquad\qquad S(0) = S_0 \ ,
\end{aligned}
\tag{2}
$$

where the co-state variable associated with the remaining stock $S(t)$ is the shadow price $\mu(t)$ 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 $G(S, Q)$ from extracting Q tons at time t are given by total benefits $U(Q)$ 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.[4] In this case, under the additional assumption that the marginal utility of income is constant, the total benefits $U(\cdot)$ that accrue from the consumption of the mineral 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.[5] 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 oil is produced by a single monopolist or by a group of colluding joint profit maximizing producers, rather than by a multitude of perfectly competitive producers, the per-period net benefits $G(S, Q)$ are given by the monopolist's per-period profit, which equals total revenue minus total costs. Total revenue $R_m(\cdot)$ at time t is given by:

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[4] 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.

[5] This holds because, assuming constant marginal utility of income:

$$P(t) = \frac{\partial U(Q(t))}{\partial Q},$$

so that the first-order conditions for the social planner's problem are the same as those that arise in perfect competition.

$$R_m(Q(t)) = D^{-1}(Q(t)) \cdot Q(t). \tag{5}$$

As a consequence, the monopolist's per-period profit $G(S,Q)$ is given by:

$$G(S,Q) = R_m(Q) - C(S,Q). \tag{6}$$

Under Cournot oligopoly, the revenue $R_j(\cdot)$ for each producer j is given by:

$$R_j(q_j(t)) = D^{-1}(Q(t)) \cdot q_j(t). \tag{7}$$

Thus, under Cournot oligopoly, the per-period profits $G_j(S, q_j)$ for each producer j is j's revenue $R_j(q_j)$ minus its costs $C_j(S_j, q_j)$:

$$G(S, q_j) = R_j(q_j) - C_j(S_j, q_j). \tag{8}$$

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

$$[\#1 \text{ perfect competition}]: \qquad P(t) = \frac{\partial C(\cdot)}{\partial Q} + \mu(t). \tag{9}$$

Under collusion, which we define as joint profit maximization, this first-order condition is:

$$[\#1 \text{ collusion}]: P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q} Q(t) + \frac{\partial C(\cdot)}{\partial Q} + \mu(t). \tag{10}$$

Under Cournot oligopoly, this first-order condition is:

$$[\#1 \text{ Cournot}]: P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q} q_j(t) + \frac{\partial C_j(\cdot)}{\partial q_j} + \mu_j(t). \tag{11}$$

If the OPEC producers collude to act jointly as the dominant cartel producer while the non-OPEC producers are the fringe, behaving either competitively or oligopolistically, then the first first-order condition for the OPEC dominant producer would be given by:

[#1 OPEC as dominant cartel producer]:

$$P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q}\left(1 + \sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}}\right) Q_{OPEC}(t) + \frac{\partial C_j\left(\cdot\right)}{\partial q_j} + \mu(t), \tag{12}$$

where $Q_{OPEC}(t)$ is the total OPEC quantity at time t and $q_j(Q_{OPEC})$ is the reaction function for the non-OPEC fringe given by the solution to either the perfect competition first-order condition (9) or the Cournot first-order condition (11), with $Q = Q_{OPEC} +_{j \notin OPEC} q_j$. Thus, OPEC producers behave as the dominant cartel producer while the non-OPEC producers are the fringe if $\sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}} \neq 0$.

A second first-order condition governs the time rate of change of the shadow price:[6]

$$[\#2]: \qquad \dot{\mu}_j(t) = \frac{\partial C\left(\cdot\right)}{\partial S} + r\mu_j(t), \tag{13}$$

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

$$\mu_j(t) = \mu_j(0)e^{rt}. \tag{14}$$

If we allow for the possibility that OPEC producers either collude to maximize joint profits or not and that non-OPEC producers behave either as Cournot oligopolists or as perfectly competitive price-takers, the general supply-side first-order condition is:[7]

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[6] The third first-order condition is the transversality condition:
$[\#3]: \qquad \lim_{t \to \infty} p(t)S(t)e^{-rt} = 0$

[7] Modeling selection into OPEC will be the subject of future work.

$$P(t) = -\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q} q_j(t) \cdot \left(1 - I_j^{OPEC}\right) - \theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q} Q_{OPEC}(t) \cdot I_j^{OPEC} + \frac{\partial C_j(\cdot)}{\partial q_j} + \mu_j(t), \tag{15}$$

where I_j^{OPEC} is an indicator variable that equals 1 if producer j is an OPEC producer and where θ_1 and θ_2 are the conduct parameters. If $\theta_1 = 0$, then the non-OPEC producers are perfectly competitive price takers; if $\theta_1 = 1$, then the non-OPEC producers are Cournot oligopolists. If $\theta_1 \in (0,1)$, this means that the non-OPEC producers exert an intermediate degree of market power. OPEC producers are perfectly colluding as joint profit maximizing producers if $\theta_2 = 1$, but are not colluding if $\theta_2 = 0$. If $\theta_2 \in (0,1)$, then the OPEC producers are colluding, but imperfectly.

If we allow for the possibility that OPEC producers either collude as the dominant producer maximizing its joint profits or not and that non-OPEC producers are the fringe, behaving either as Cournot oligopolists or as perfectly competitive price-takers, the general supply-side first-order condition is:

$$\begin{aligned} P(t) \;=\; & \\ & -\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q} q_j(t) \cdot \left(1 - I_j^{OPEC}\right) \\ & -\theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q} \left(1 + \sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}}\right) Q_{OPEC}(t) \cdot I_j^{OPEC} \\ & + \frac{\partial C_j(\cdot)}{\partial q_j} + \mu_j(t). \end{aligned} \tag{16}$$

If the OPEC producers collude as the dominant producer maximizing its joint profits ($\theta_2 = 1$) and the non-OPEC producers are the fringe, behaving either as Cournot oligopolists or as perfectly competitive price-takers, then the residual demand $D_{OPEC}(P(t))$ faced by OPEC producers is given by the difference between the market demand and the fringe supply:

$$D_{OPEC}(P(t)) = D(P(t)) - \sum_{j \notin OPEC} q_j(P(t)), \tag{17}$$

which, after taking the derivative of both sides with respect to price P and rearranging, yields that the residual demand elasticity ε_{OPEC} faced by the OPEC producers is the following function of the market demand elasticity ε_M and the fringe supply elasticity η:

$$\varepsilon_{OPEC} = \frac{Q}{Q_{OPEC}}\varepsilon_M - \frac{\sum_{j \notin OPEC} q_j}{Q_{OPEC}}\eta. \tag{18}$$

Thus, since $Q > Q_{OPEC}$ and the supply elasticity η is non-negative, if the OPEC producers collude as the dominant producer and the non-OPEC producers are the fringe, behaving either as Cournot oligopolists or as perfectly competitive price-takers, then the residual demand faced by OPEC is more elastic than market demand.

4 Data

We use annual data on oil price and country-level data on extraction and cost for oil over the period 1970 to 2004 from previously unpublished World Bank data.[8] The analysis does not extend beyond 2004 due to data availability constraints, particularly for the cost data, and because OPEC spare capacity was low in 2005 and 2006 (EIA, 2016b), suggesting that a model of more recent years may need to also include capacity constraints due to well drilling. Table 1 presents summary statistics.[9]

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[8] 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; we use this formula to calculate average costs.

[9] The units in the data set are in terms of tons of oil. The number of barrels of crude oil per metric ton varies by region and over time, ranging from between 6.6 to 8.1 over 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, we kept the units in tons instead of converting them to barrels for the econometric analysis. In Table 1, oil price is reported both in units of 1982-1984 US $ per ton, and also in units of 1982-1984 US $ per barrel using a conversion rate of 7.33 barrels per ton.

The use of annual data is appropriate for our analysis because it enables me 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. Moreover, while production may be capacity constrained at a monthly level until more wells are drilled (Anderson, Kellogg and Salant, 2018), production is less likely to be constrained at an annual level since during the time period of the data set it took about 3 months (i.e., much less than a year) to initiate and complete a drilling program (Hendricks and Porter, 1996); as a consequence, producers are likely able to respond at an annual level to any capacity constraints they might face at a monthly level by drilling more wells. Moreover, OPEC spare capacity, which the Energy Information Administration defines as the volume of production that can be brought on within 30 days and sustained for at least 90 days (EIA, 2016b), has been high for most of the period of the data set, and was around 10 million barrels per day in 1985 (Fattouh, 2006), suggesting that capacity constraints may have been less of an issue at an annual level during the period analyzed in this paper.[10] As we show in our empirical model below, annual data on price, extraction, and cost, along with country fixed effects, enables me to best measure market power using the general supply-side first-order condition (16).

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 including oil, Atewamba (2011, 2013) finds that he cannot reject that marginal extraction cost is equal to average extraction cost at a 5% level for oil. He concludes that it should therefore be acceptable to use the average extraction cost data as a proxy for marginal extraction cost. Atewamba and Nkuiya (2017) similarly cannot reject that marginal extraction cost is equal to average extraction cost at a 5% level over the time period of the data set for oil. Atewamba

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[10] OPEC spare capacity was low in 2005 and 2006 (EIA, 2016b), but this occurred after the period of the data set, which spans 1970-2004.

(2011, 2013) and Atewamba and Nkuiya (2017) use the same data for oil 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.

We control for any time-invariant country-specific differences between average costs and marginal costs by including country fixed effects in the empirical estimation. As explained below, the error term in the regression captures any additional difference between average costs and marginal costs. Because differences between average costs and marginal costs absorbed in the error term may be correlated with quantity, we instrument for quantity in the empirical estimation.

5 Empirical Estimation

The empirical model allows for the possibility that OPEC producers either collude (by maximizing the joint profits of all the OPEC producers) or not and that non-OPEC producers behave either as Cournot oligopolists or as perfectly competitive price-takers, possibly as the fringe. We estimate the following empirical specification of the general supply-side first-order condition (16) from the theory model:

$$P_t = \widetilde{\theta}_1 q_{jt} \cdot \left(1 - I_j^{OPEC}\right) + \widetilde{\theta}_2 Q_{OPEC,t} \cdot I_j^{OPEC} + \beta AC_{jt} + \mu_{j0} e^{rt} + \alpha_j + \nu_{jt}, \tag{19}$$

where P_t is the real price of oil in year t, q_{jt} is the quantity of production in country j in year t, $Q_{OPEC,t}$ is the total OPEC quantity in year t, AC_{jt} is the average cost in country j in year t, α_j is a country fixed effect, ν_{jt} is an error term, $\theta = \left(\widetilde{\theta}_1, \widetilde{\theta}_2, \beta, \mu_{j0}\right)$ are the parameters to be estimated, and the coefficients $\widetilde{\theta}_1$ and $\widetilde{\theta}_2$ are the following functions of the conduct parameters θ_1 and θ_2:

$$\begin{aligned}
\widetilde{\theta}_1 &= -\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q} && (20)\\
\widetilde{\theta}_2 &= -\theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q} \left(1 + \sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}}\right). && (21)
\end{aligned}$$

Any time-invariant country-specific differences between average costs and marginal costs are captured by the country fixed effects α_j. The error term ν_{jt} in the general supply-side first-order condition captures any additional time-varying difference between average costs and marginal costs that are common across countries.[11]

We focus on the cases where non-OPEC producers are either price-takers or oligopolists,

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[11] The effects of other simplifying assumptions of the model, including the assumptions of no uncertainty and no exploration, which were made for analytic tractability and because of data limitations, are absorbed in the error term as well.

and where OPEC producers are either colluding or not, as these are the market structure scenarios most commonly considered in the literature and most likely to reflect the reality of the petroleum market. Results of models that allowed for other possible market structures such as collusion among non-OPEC producers and/or oligopolistic behavior among OPEC producers (not shown) yielded unrealistic parameter values such as a negative coefficient on average costs, which corroborates this view.

To estimate equation (19), we run a two-stage least squares regression of world price on quantity for non-OPEC producers, total OPEC quantity for OPEC producers, average cost, 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 μ_{j0} on this regressor is the country-specific initial shadow price in 1970 under the assumption that there are no stock effects. Differences in the country-specific shadow price μ_{j0} in 1970 therefore reflect differences in the initial stock of reserves S_0 across countries. I set the discount rate r to 5% for the base case scenario, and vary the value of r between 2% and 10% 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, 2016b). 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.[12] We therefore allow for the possibility of stock effects as well as for differences in reserves across countries.

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

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[12] 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 oil price, takes on only one value each year.

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, and because differences between average costs and marginal costs absorbed in the error term may be correlated with quantity, quantity is endogenous in the supply equation given by the supply-side first-order condition, and therefore must be instrumented. Domestic extraction quantity in non-OPEC countries is instrumented with country population. Country population is a shifter for the demand in non-OPEC countries, and, since much of domestic production is consumed domestically in non-OPEC countries (EIA, 2016a), country population is correlated with non-OPEC quantity but does not affect price except through its effect on quantity, and thus serves as a good instrument for quantity in non-OPEC countries in the supply equation.

Total OPEC extraction quantity is instrumented with OPEC country population, world population, and real world GDP. World population is a shifter for world demand that is correlated with total OPEC quantity but does not affect price except through its effect on quantity, and thus serves as a good instrument for total OPEC quantity in the supply equation. Similarly, world GDP is a shifter for world demand that is correlated with total OPEC quantity and, since the oil industry only constitutes a small fraction of world GDP[13] (World Bank, 2016b), world GDP does not affect price except through its effect on quantity; thus, world GDP serves as a good instrument for total OPEC quantity in the supply equation. Moreoever, as OPEC's domestic oil consumption has increased to seven-fold in 40 years, constituting one-fourth of OPEC production and almost on par with oil consumption in China (Gately, Al-Yousef and Al-Sheikh, 2013), OPEC country population is a shifter for demand in OPEC countries that is correlated with total OPEC quantity but does not affect price except through its effect on quantity, and thus also serves as a good instrument for total OPEC quantity in the supply

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[13] Oil rents constituted only 0.5% and 2.5% of world GDP in 1970 and 2014, respectively (World Bank, 2016).

equation. GDP and population data are from the World Bank World Development Indicators database.

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.

Table 2 presents the results from the first-stage regressions. The coefficient on country population is statistically significant in the first-stage regression on quantity in non-OPEC countries, with a first-stage F-statistic of 45.58. The joint F-statistic for the instruments country population, world population, and world GDP in the first-stage regression of total OPEC quantity is 18.55. Although only the coefficient on world GDP is significant in the first-stage regression of total OPEC quantity, all three instruments are needed in order for the first-stage F-statistic on the instruments to be greater than 10. Additionally, as seen in Table 3, the instruments pass Anderson-Rubin 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.

The coefficient on quantity in non-OPEC producers is $\widetilde{\theta_1} = -\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q}$, which is a product of the market conduct parameter θ_1 and the (absolute value of the) slope of the inverse demand curve. Similarly, the coefficient on OPEC quantity is $\widetilde{\theta_2} = -\theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q} \left(1 + \sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}}\right)$, which is a product of the market conduct parameter θ_2, the (absolute value of the) slope of the inverse demand curve and one plus the sum of the slopes of the reaction curves of the non-OPEC fringe producers. If the coefficient $\widetilde{\theta_1}$ on quantity produced for non-OPEC producers is statistically significant, then $\theta_1 > 0$ and therefore the non-OPEC producers exhibit market power as (possibly imperfect) Cournot oligopolists; otherwise, $\theta_1 = 0$ and they behave as price-takers. Similarly, if the coefficient $\widetilde{\theta_2}$ on total OPEC quantity for OPEC producers is statistically significant, then $\theta_2 > 0$ and the OPEC producers are colluding, possibly imperfectly; otherwise, $\theta_2 = 0$ and they are not colluding. Since demand is downward-sloping, we expect the coefficients on quantity for non-OPEC producers and total OPEC quantity for OPEC producers to be positive when $\theta_1 > 0$ and $\theta_2 > 0$, respectively, when the sum of the slopes of the reaction functions of the non-OPEC fringe greater than -1: $\sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}} > -1$.[14]

Similar to Sullivan (1985), who estimates an upper bound on the degree of collusion without relying on the identification of a demand curve, we use an approach to testing market conduct that does not rely on the identification of a demand curve. As oil demand is particularly difficult to estimate (Lin, 2011), an advantage of our approach is that our results do not hinge on our correctly specifying, identifying, and estimating oil demand, but instead merely require the assumption that oil demand is downward-sloping.

Previous studies of oil prices suggest that the world oil market has changed over time (Zaklan, Abrell and Neumann, 2011; van der Lind, 2013; Lee, List and Strazicich, 2006; Pindyck, 1999). In order to allow for the possibility that market structure, the slope of oil demand, and/or demand elasticities may have changed over the period 1970-2004, and also to allow for there to be other structural differences in market conduct over time due to changes in exploration or technology, we also run the model allowing the conduct parameters θ_1 and θ_2 to vary by decade.

Table 3 presents the results from estimating the model. Specification (1) allows for the possibility that OPEC producers either colludes or not and that non-OPEC producers behave either as Cournot oligopolists or as perfectly competitive price-takers, possibly as the fringe. The coefficient on total OPEC quantity for OPEC producers is statistically significant, which means that the OPEC producers colluded. Moreover, the coefficients are positive, which is consistent with a downward-sloping demand function. The coefficient on quantity for non-OPEC producers is not significant in specification (1), so we cannot reject that the non-OPEC producers behaved as perfectly competitive price-takers.

Specification (2) allows the conduct parameters and demand elasticities to vary by decade. The coefficient on quantity for non-OPEC producers is significant in each decade, which sug-

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[14] For example, when demand and costs are linear, the sum of the slopes of the reactions functions of the non-OPEC fringe is greater than -1 when $\sum_{j \notin OPEC} \frac{\partial p_j}{\partial Q_{OPEC}} \leq -\frac{\partial D^{-1}(Q(t))}{\partial Q}$. The assumption of linear costs (i.e., that marginal costs equal average costs) is reasonable for the reasons listed above.

gests that the non-OPEC producers behaved oligopolistically. The coefficient on total OPEC quantity for OPEC producers is significant in each decade, which suggests that OPEC producers colluded.

In both specifications, as expected, the coefficient on average costs is significant and positive.

To test whether a Hotelling model is appropriate for the world oil market, we test the significance of the shadow price by testing the joint significance of the coefficients μ_{j0} on the country fixed effects interacted with e^{rt}. In both specifications, the shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is.

If the OPEC producers are colluding perfectly ($\theta_2 = 1$) and if the non-OPEC producers are Cournot oligopolists ($\theta_1 = 1$) and not behaving as fringe producers $\left(\sum_{j \notin OPEC} \frac{\partial q_j(Q_{OPEC}(t))}{\partial Q_{OPEC}} = 0\right)$, then the coefficients $\widetilde{\theta_1}$ and $\widetilde{\theta_2}$ on quantity on non-OPEC producers and total OPEC quantity for OPEC producers, respectively, should be equal to each other and should yield the (absolute value of the) slope of the inverse demand curve. However, if the OPEC producers collude as the dominant producer ($\theta_2 = 1$) and the non-OPEC producers are the fringe, behaving either as Cournot oligopolists or as perfectly competitive price-takers, then the residual demand elasticity ε_{OPEC} faced by the OPEC producers would be more elastic than the market demand elasticity ε_M, and their relationship would be given by equation (18). As seen in Table 3, results of a test that the coefficients $\widetilde{\theta_1}$ and $\widetilde{\theta_2}$ on quantity on non-OPEC producers and total OPEC quantity for OPEC producers, respectively, are equal to each other are rejected at the 1% level in each decade of the analysis by decade, thus providing evidence that the non-OPEC producers are fringe producers. Since the coefficient on quantity for non-OPEC producers is significant in each decade, which suggests that the non-OPEC producers behaved oligopolistically, the results by decade therefore support OPEC countries colluding as the dominant producer and non-OPEC countries behaving as an oligopolistic fringe.

Table 4 presents the elasticities for market demand, residual demand and the oligopolistic fringe supply implied by our results if OPEC countries colluded as the dominant producer and non-OPEC countries behaved as an oligopolistic fringe. The elasticities are evaluated at the respective mean price and quantity. The magnitudes of the reported market demand elasticities and residual demand elasticities are upper bounds because there is a possiblity for intermediate forms of market power and collusion: i.e., where $\theta_1 \in (0,1)$ and $\theta_2 \in (0,1)$ rather than $\theta_1 = 1$ and $\theta_2 = 1$. According to the results by decade, market demand for oil is inelastic; its elasticity declines from -0.022 in the 1970s to -0.005 for the recent period 1990-2004. As expected, the residual demand faced by OPEC is more elastic than market demand; its elasticity ranges from -1.82 in the 1970s to -0.96 over the period 2000-2004. The supply elasticity of the oligopolistic non-OPEC fringe ranges from 0.24 over the period 2000-2004 to 1.64 in the 1970s.

Table 5a presents the results from estimating the model using different discount rates r between 2% and 10%; Table 5a presents analogous results from allowing the behavior of the OPEC producers and the non-OPEC producers to vary by decade. 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. However, some point estimates of the coefficients $\widetilde{\theta}_1$ and $\widetilde{\theta}_2$ on quantity on non-OPEC producers and total OPEC quantity for OPEC producers, respectively, decrease as the discount rate r increases, which means that the point estimate of the demand elasticity decreases in magnitude as the discount rate increases. This result suggests that consumers may be less elastic and therefore may not respond as much to changes in price when they discount the future more and their time horizon is therefore shorter. For all discount rates, the shadow prices are jointly significant, which confirms that a dynamic model that incorporates the shadow price is the appropriate model for the world oil market.

6 Conclusion

This paper revisits an old but important issue that has long interested economists: what is the market structure of the world oil market and, in particular, has OPEC been able to function as an effective cartel? This issue has been the focus of attention of numerous studies going back to at least the early 1980s. While results have been found in many directions, a recent survey article by Baumeister and Killian (2016) concludes that 'the literature has not been kind to the view that OPEC since 1973 has acted as a cartel' (p.145).

This paper estimates a dynamic model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004, allowing for the possibility that market structure and demand elasticities may have changed over time during this time period. Results of the analysis by decade support OPEC countries colluding as the dominant cartel producer and non-OPEC countries behaving as an oligopolistic fringe. Market demand has become more inelastic over time over the period of study.

Oligopolistic behavior among non-OPEC producers in the 1970s and 1980s is consistent with Roncaglia (1985), whose study of the international oil market from its inception to the early 1980s characterized the market as that of trilateral oligopoly. In his testing among cartel, competitive, target revenue, and property rights models, Griffin (1985) finds that over 1971-1983 the competitive model could not be rejected for 10 of 11 non-OPEC producers. His result is not inconsistent with the result of this paper, however, because oligopoly was not one of the models considered.

Collusion among OPEC producers is consistent with the results of Griffin (1985), who finds that over 1971-1983, the partial market-sharing cartel model could not be rejected for all 11 countries; and with the results of Smith (2005), who applies a production-based approach for examining alternative hypotheses, and finds strong evidence of cooperative behavior among OPEC members. Collusion among OPEC producers in the earlier years of the data set are also consistent with the characterization in Zellou and Cuddington (2012), who draws upon

Hamilton (2011) and Yergin (1991), that the years of 1973-1996 represented the age of OPEC. Our results are also consistent with those of Golombek, Irarrazabal and Ma (2018), who find that OPEC exercised market power during the period 1986-2016.

According to the results by decade, market demand for oil is inelastic. The low magnitudes of the oil demand elasticity are consistent with a recent study by Cooper (2003), who estimates long- and short-run elasticities of demand for crude oil for 23 countries over the period 1971-2000, and finds that demand is highly inelastic, with the short-run elasticity ranging from -0.109 to -0.016. The decline in the elasticity of oil over time that we find is consistent with the results of Hughes et al. (2008), who find that the short-run gasoline price elasticity in the U.S. shifted down considerably from a range of -0.21 to -0.34 in the late 1970s to -0.034 to -0.077 in the early 2000s. The decline in the elasticity of oil over time that we find is also consistent with the results of Baumeister and Peersman (2013), who find a substantial decline in the short-run price elasticity of oil demand since the mid-1980s.

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. Second, this paper builds upon existing empirical studies of the petroleum market by addressing the identification problem that arises in empirical analyses of supply and demand. The third contribution is that this paper develops a Hotelling model that enables one to test for the market conduct of OPEC and non-OPEC producers. The estimated shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is.

The Hotelling model developed and estimated in this paper accounts for the nonrenewable nature of the resource; addresses the identification problem that arises in empirical analyses of supply and demand; enables one to test for the market conduct of OPEC and non-OPEC producers; and yields results consistent with some of the more qualitative analyses of experts on the world oil market (see e.g., Rocaglia, 1985; Yergin, 1991).

Future possible avenues of research include allowing for uncertainty, exploration, capacity constraints, technological progress, stock effects, and/or drilling, all of which were assumed away in this paper for analytic tractability and due to data limitations. We hope in the future to find data to enable me to incorporate these considerations. In future work, we hope also to develop a model that incorporates both dynamics arising from the nonrenewable nature of the resource and dynamics arising from efficient tacit collusion; in this paper, We are unable to add the year fixed effects suggested by Puller (2009) to address efficient tacit collusion because the dependent variable, the annual real world oil price, takes on only one value each year. We also hope in future work to develop and estimate a structural econometric model of the dynamic game among oil producers, building on previous theoretical models of such dynamic games (Karp and Perloff, 1993; Karp, 1984; Karp, 1991; Karp and Newbery, 1993; van der Lind, 2013; Perloff, Karp and Golan, 2008; Rauscher, 2012), by assuming a Markov Perfect Equilibrium that better characterizes the equilibrium strategies of firms as functions of their reserves. Kheiravar, Lin Lawell and Jaffe (2019) develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market that allows firms that are at least partially state-owned to have objectives other than profit maximization alone.

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TABLE 1. Summary statistics

Variable	# obs	mean	s.d.	min	max
oil price (1982-1984 US $ per ton)	35	131.78	72.76	33.49	327.74
oil price (1982-1984 US $ per barrel, assuming 7.33 barrels/ton)	35	17.98	9.93	4.57	44.71
oil quantity extracted (million tons)	2659	35.71	78.57	0.0007	569.48
OPEC quantity extracted (million tons)	35	1237.11	214.09	803.67	1542.12
world quantity extracted (million tons)	35	5079.48	1645.19	2004.06	6876.84
average cost of extraction (1982-1984 US $ per ton)	2659	31.17	21.21	3.18	103.87
country population (million)	2659	55.25	156.05	0.11	1296.16
world population (million)	35	5011.82	820.08	3678.38	6363.20
world GDP (1982-1984 trillion US $)	35	14.6	3.85	7.45	21.9

Notes: The data consists of annual country-level data over the period 1970-2004. There are 103 countries producing oil in at least one year of the time period. The number of barrels of crude oil per metric ton varies by region and over time, ranging from 6.6 to 8.1 over the period 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, I kept the units in tons instead of converting them to barrels for the econometric analysis. Oil price is reported above both in units of 1982-1984 US $ per ton, and also in units of 1982-1984 US $ per barrel using a conversion rate of 7.33 barrels per ton.

TABLE 2. First-stage regressions

	Dependent variable is:	
	oil quantity (million tons) for non-OPEC countries (1)	*total OPEC oil quantity (million tons) for OPEC countries* (2)
country population (million) * is not an OPEC country	0.31 ***	-0.73 *
	(0.03)	(0.31)
country population (million) * is an OPEC country	-0.23	-15.20
	(0.15)	(11.09)
world population (million) * is an OPEC country	-0.00	0.06
	(0.00)	(0.03)
world GDP (1982-1984 billion US $) * is an OPEC country	0.00	5.32 E-11 ***
	(0.00)	(1.06 E-11)
average cost of extraction (1982-1984 US $ per ton)	0.01	0.41 **
	(0.04)	(0.14)
country fixed effects	Y	Y
country fixed effects * e^{rt}	Y	Y
joint F-statistic for instruments	45.58	18.55
# observations	2659	2659

Notes: Robust standard errors in parentheses. The number of barrels of crude oil per metric ton varies by region and over time, ranging from 6.6 to 8.1 over the period 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, I kept the units in tons instead of converting them to barrels. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

TABLE 3. IV Results

Dependent variable is real price of oil (1982-1984 US $ per ton)	(1)	(2)
quantity (million tons) * is not an OPEC country	0.50	
	(0.67)	
1970-1979		2.00 *
		(0.80)
1980-1989		2.74 ***
		(0.70)
1990-1999		2.70 ***
		(0.80)
2000-2004		3.84 ***
		(0.92)
OPEC quantity (million tons) * is an OPEC country	0.05 **	
	(0.02)	
1970-1979		0.05 **
		(0.02)
1980-1989		0.14 ***
		(0.02)
1990-1999		0.05 ***
		(0.01)
2000-2004		0.09 ***
		(0.02)
average cost of extraction (1982-1984 US $ per ton)	2.83 ***	2.68 ***
	(0.12)	(0.15)
country fixed effects	Y	Y
country fixed effects * e^{rt}	Y	Y
p-value (Pr > F)	0.00 ***	0.00 ***
# observations	2659	2659
Results of weak-instrument-robust inference tests		
p-value of Anderson-Rubin Wald F-test	[0.007] **	[0.000] ***
p-value of Anderson-Rubin Wald Chi-sq test	[0.004] *	[0.000] ***
*Results of joint test of country fixed effects * e^{rt}*		
p-value (Pr > chi2)	[0.000] ***	[0.000] ***
Result of test that coefficient on total OPEC quantity for OPEC producers is equal to the coefficient on quantity for non-OPEC producers		
p-value (Pr > chi2)	[0.493]	
1970-1979		[0.014] **
1980-1989		[0.000] ***
1990-1999		[0.001] ***
2000-2004		[0.000] ***

Notes: Robust standard errors in parentheses. Quantity in non-OPEC countries is instrumented with country population. Quantity in OPEC countries and total OPEC quantity are instrumented with country population, world population, and real world GDP. The number of barrels of crude oil per metric ton varies by region and over time, ranging from 6.6 to 8.1 over the period 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, I kept the units in tons instead of converting them to barrels. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

TABLE 4. Elasticities

	(1)	(2)
market demand elasticity	-0.05 (0.07)	
1970-1979		-0.022 * (0.009)
1980-1989		-0.013 *** (0.003)
1990-1999		-0.005 *** (0.002)
2000-2004		-0.005 *** (0.001)
residual demand elasticity	-2.13 * (0.85)	
1970-1979		-1.82 * (0.73)
1980-1989		-1.34 *** (0.19)
1990-1999		-1.43 *** (0.29)
2000-2004		-0.96 *** (0.32)
oligopolistic fringe supply elasticity	0.62 * (0.29)	
1970-1979		1.64 * (0.67)
1980-1989		0.29 *** (0.04)
1990-1999		0.36 ** (0.07)
2000-2004		0.24 *** (0.05)

Notes: Robust standard errors in parentheses. The calculations are made assuming that OPEC producers collude perfectly and that non-OPEC producers behave as Cournot oligopolists. If OPEC producers collude imperfectly or non-OPEC producers behave as imperfect Cournot oligopolists, then the reported magnitudes of the residual demand elasticity and the market demand elasticity, respectively, 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 5a. IV Results for Different Discount Rates *r*

	Dependent variable is real price of oil (1982-1984 US $ per ton) (1)					
	$r = 2\%$	$r = 4\%$	$r = 5\%$	$r = 6\%$	$r = 8\%$	$r = 10\%$
quantity (million tons) * is not an OPEC country	0.57	0.62	0.50	0.37	0.11	-0.13
	(0.92)	(0.73)	(0.67)	(0.63)	(0.58)	(0.55)
OPEC quantity (million tons) * is an OPEC country	0.05 **	0.05 **	0.05 **	0.05 **	0.04 *	0.04 *
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
average cost of extraction (1982-1984 US $ per ton)	2.88 ***	2.84 ***	2.83 ***	2.83 ***	2.84 ***	2.86 ***
	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
country fixed effects	Y	Y	Y	Y	Y	Y
country fixed effects * e^{rt}	Y	Y	Y	Y	Y	Y
p-value (Pr > F)	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***
# observations	2659	2659	2659	2659	2659	2659
	*Results of joint test of country fixed effects * e^{rt}*					
p-value (Pr > chi2)	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***

Notes: Robust standard errors in parentheses. Quantity in non-OPEC countries is instrumented with country population. Quantity in OPEC countries and total OPEC quantity are instrumented with country population, world population, and real world GDP. The number of barrels of crude oil per metric ton varies by region and over time, ranging from 6.6 to 8.1 over the period 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, I kept the units in tons instead of converting them to barrels. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

TABLE 5b. IV Results by Decade for Different Discount Rates *r*

	Dependent variable is real price of oil (1982-1984 US $ per ton)					
			(2)			
	$r = 2\%$	$r = 4\%$	$r = 5\%$	$r = 6\%$	$r = 8\%$	$r = 10\%$
quantity (million tons) * is not an OPEC country						
1970-1979	3.35 *	2.46 **	2.00 *	1.59 *	0.94	0.46
	(1.38)	(0.88)	(0.80)	(0.76)	(0.72)	(0.70)
1980-1989	4.10 **	3.22 ***	2.74 ***	2.32 ***	1.64 **	1.15 *
	(1.41)	(0.81)	(0.70)	(0.63)	(0.67)	(0.55)
1990-1999	4.18 *	3.26 ***	2.70 ***	2.19 **	1.33 *	0.67
	(1.71)	(0.95)	(0.80)	(0.70)	(0.61)	(0.58)
2000-2004	5.12 **	4.37 ***	3.84 ***	3.33 ***	2.43 ***	1.70 **
	(1.89)	(1.09)	(0.92)	(0.81)	(0.69)	(0.64)
OPEC quantity (million tons) * is an OPEC country						
1970-1979	0.06 ***	0.05 ***	0.05 **	0.04 **	0.04 **	0.04 *
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
1980-1989	0.15 ***	0.14 ***	0.14 ***	0.13 ***	0.12 ***	0.12 ***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
1990-1999	0.06 **	0.06 ***	0.05 ***	0.05 ***	0.04 **	0.04 *
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
2000-2004	0.08 ***	0.09 ***	0.09 ***	0.09 ***	0.09 ***	0.09 ***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
average cost of extraction (1982-1984 US $ per ton)	2.85 ***	2.73 ***	2.68 ***	2.65 ***	2.62 ***	2.62 ***
	(0.19)	(0.16)	(0.15)	(0.15)	(0.14)	(0.14)
country fixed effects	Y	Y	Y	Y	Y	Y
country fixed effects * e^{rt}	Y	Y	Y	Y	Y	Y
p-value (Pr > F)	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***
# observations	2659	2659	2659	2659	2659	2659
	*Results of joint test of country fixed effects * e^{rt}*					
p-value (Pr > chi2)	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***	[0.00] ***

Notes: Robust standard errors in parentheses. Quantity in non-OPEC countries is instrumented with country population. Quantity in OPEC countries and total OPEC quantity are instrumented with country population, world population, and real world GDP. The number of barrels of crude oil per metric ton varies by region and over time, ranging from 6.6 to 8.1 over the period 1980-2004 (EIA, 2015). Since the conversion rate was not available for each county in each year of the data set, I kept the units in tons instead of converting them to barrels. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.