

# Estimating strategic interactions in petroleum exploration

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## Abstract

When individual petroleum-producing firms make their exploration decisions, information externalities and extraction externalities may lead them to interact strategically with their neighbors. If they do occur, strategic interactions in exploration would lead to a loss in both firm profit and government royalty revenue. Since these strategic interactions would be inefficient, changes in the government offshore leasing policy would need to be considered. The possibility of strategic interactions thus poses a concern to policy-makers and affects the optimal government policy. This paper examines whether these inefficient strategic interactions take place in U.S. federal lands in the Gulf of Mexico. In particular, it analyzes whether a firm's exploration decisions depend on the decisions of firms owning neighboring tracts of land. A discrete response model of a firm's exploration timing decision that uses variables based on the timing of a neighbor's lease term as instruments for the neighbor's decision is employed. The results suggest that strategic interactions do not actually take place, at least not in exploration, and therefore that the current parameters of the government offshore leasing policy do not lead to inefficient petroleum exploration.

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# 1 Introduction

Exploration is the first stage of petroleum production: when a firm acquires a previously unexplored tract of land, it must first decide whether and when to invest in the drilling rigs needed to begin exploratory drilling. If firms own leases to neighboring tracts of land that may be located over a common pool of reserve, there are two types of externalities that add a strategic (or non-cooperative)<sup>2</sup> dimension to firms' exploration timing decisions and may render these decisions socially inefficient.<sup>3</sup>

The first type of externality is an *information externality*: if tracts are located over a common pool or share common geological features so that their ex post values are correlated, then firms learn information about their own tracts when other firms drill exploratory wells on neighboring tracts (Hendricks & Porter, 1996). The information externality is socially inefficient because it may cause firms to play a non-cooperative timing game that leads them to inefficiently delay production, since the possibility of acquiring information from other firms may further enhance the option value to waiting. If firms are subject to a lease term by the end of which they must begin exploratory drilling, or else relinquish their lease, then the information externality would result in too little exploration at the beginning of the lease term and duplicative drilling in the final period of the lease (Hendricks & Porter, 1996; Porter, 1995). In contrast, the optimal coordinated plan would entail a sequential search in which one tract would be drilled in the first period and, if productive, a neighboring tract is drilled in the next (Porter, 1995).

A second type of externality is an *extraction externality*: when firms have competing rights to a common-pool resource, strategic considerations may lead them to extract at an inefficiently high rate (Libecap & Smith, 1999a; Libecap & Wiggins, 1985). When oil is extracted too quickly, it may cause a collapse in the formation being extracted from,

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<sup>2</sup>In this paper, I use the terms "strategic" and "non-cooperative" interchangeably.

<sup>3</sup>In my broad definition of an externality, I say that an externality is present whenever a non-coordinated decision by individual firms is not socially optimal.

thus collapsing the pipe and decreasing the total amount of oil extracted (Kenny McMinn, Offshore District Production Manager, Apache Corporation, personal communication, 22 January 2004).

Owing to both information and extraction externalities, the dynamic decision-making problem faced by a petroleum-producing firm is not merely a single-agent problem, but rather can be viewed as a multi-agent, non-cooperative game in which firms behave strategically and base their exploration policies on those of their neighbors. Both externalities suggest that firms will be more likely to drill when its neighbors are drilling as well. The information externality leads firms to drill when neighbors drill because a neighbor's drilling reveals to the firm that the neighbor thinks its tract is worth exploring, therefore suggesting that the firm's own tract may be worth exploring as well. The extraction externality leads firms to drill when neighbors drill because a firm wants to be able to extract from the common pool resource before its neighbor does.

Both externalities lead to strategic interactions that are socially inefficient. The information externality leads to an inefficient delay in exploration. The extraction externality leads to excessively high extraction rates and less total oil extracted. Both types of strategic behavior lead to lower profits for the petroleum-producing firms and lower royalty revenue for the federal government. It is therefore important to analyze whether these strategic interactions place, and therefore whether policies that can mitigate the strategic interactions should be implemented.

Since 1954, the U.S. government has leased tracts from its federal lands in the Gulf of Mexico to firms interested in offshore petroleum production by means of a succession of lease sales. A lease sale is initiated when the government announces that an area is available for exploration, and nominations are invited from firms as to which tracts should be offered for sale. In a typical lease sale, over a hundred tracts are sold simultaneously in separate first-price, sealed-bid auctions. Many more tracts are nominated than are sold, and the nomination process probably conveys little or no information (Porter, 1995). A

tract is typically a block of 5000 acres or 5760 acres (Marshall Rose, Minerals Management Service, personal communication, 9 November 2005). The size of a tract is often less than the acreage required to ensure exclusive ownership of any deposits that may be present (Hendricks & Kovenock, 1989), and tracts within the same area may be located over a common pool (Hendricks & Porter, 1993). To date, the largest petroleum field spanned 23 tracts. Depending on water depth, 57-67 percent of the fields spanned more than one tract and 70-79 percent spanned three or fewer tracts (Marshall Rose, Minerals Management Service, personal communication, 31 March 2005). Because neighboring tracts of land may share a common pool of petroleum reserve, information and extraction externalities that lead firms to interact strategically may be present. As a consequence, petroleum production on the federal leases may be inefficient.

In this paper, I analyze whether firms' exploration timing decisions on U.S. federal lands in the Gulf of Mexico depend on the exploration timing decisions of firms owning neighboring tracts of land. To answer this question, I estimate a discrete response model of a firm's exploration investment decision using variables based on the timing of a neighbor's lease term as instruments for the neighbor's decision.

The research presented in this paper is important for several reasons. First, an empirical analysis of investment timing decisions enables one to examine whether the strategic interactions that are predicted in theory actually occur in practice. Second, the estimation of strategic interactions, especially those that arise in a spatial context, is of methodological interest. Third, my results have implications for leasing policy: if the strategic effects and externalities turn out to be large, then the program by which the U.S. government leases tracts to firms may be inefficient, and possible modifications should be considered.

The exploration timing game in offshore petroleum production in the Gulf of Mexico has been examined in a seminal series of papers by Kenneth Hendricks, Robert Porter and their co-authors (see e.g. Hendricks & Kovenock, 1989; Hendricks & Porter, 1993; Hendricks & Porter, 1996). These papers focus on the information externality associated with exploratory

drilling. They analyze this externality and the learning and strategic delay that it causes by developing theoretical models of the exploration timing game. In addition, Hendricks and Porter (1993, 1996) calculate the empirical drilling hazard functions for cohorts in specific areas, and study the determinants of the exploration timing decision and of drilling outcomes. According to their results, equilibrium predictions of plausible non-cooperative models are reasonably accurate and more descriptive than those of cooperative models of drilling timing.

The reduced-form discrete response model of firms' exploration timing decision presented in this paper improves upon that of Hendricks and Porter by using instruments to address endogeneity problems and by defining neighbors based on geographic distances rather than by the area boundaries drawn by the federal government.

The results do not indicate that a firm's exploratory drilling decision depends on those of its neighbors. Information and extraction externalities do not appear to induce firms to interact strategically on net during exploration, possibly because these externalities do not become important until later stages of production.

The balance of the paper proceeds as follows. Section 2 presents the econometric model. Section 3 describes the data. The results are presented in Section 4. Section 5 concludes.

## 2 Model

Let  $t$  denote the time since the lease sale. At the beginning of each period  $t$ , the owner of each tract  $i$  must decide whether to invest in exploration at time  $t$ . For each period  $t$ , all firms make their time- $t$  investment decisions simultaneously. Let  $I_{it}^e$  be an indicator for whether exploration began on tract  $i$  at time  $t$ . Let  $J_{it}$  be the number of neighbors that tract  $i$  has at time  $t$ .

Let  $\pi(\cdot)$  denote a firm's payoff to exploring. This payoff is the expected revenue from exploring the tract minus the cost of exploration. The firm's expected revenue depends on

the firm's time- $t$  estimate of the quantity of reserves on its tract that it can extract, and therefore depends exogenous covariates  $x_{it}$  such as the estimated pre-sale value of the tract and the winning bid of the tract, both of which measure the expected value of the tract prior to the neighbors' exploration, and on the fraction  $n_{it}$  of neighbors  $j$  who explored at time  $t - 1$ :

$$n_{it} = \frac{\sum_{j=1}^{J_{it}} I_{j,t-1}^e}{J_{it}}. \quad (1)$$

The firm uses the fraction of neighbors who explore to update its prior on the expected value of exploration.

As formalized in Lin's (2007) structural model of the firm's dynamic decision-making problem, a firm will invest in the drilling rigs needed to begin exploratory drilling at time  $t$  if its profits from exploration exceed the continuation value from waiting. The value  $V(\cdot)$  of an unexplored tract  $i$  at time  $t$  is therefore given by:

$$V(n_{it}, x_{it}) = \max\{\pi(n_{it}, x_{it}), \beta V^c(n_{it}, x_{it})\}, \quad (2)$$

where  $\beta$  is the discount factor and  $V^c(n_{it}, x_{it})$  is the continuation value to waiting instead of exploring at time  $t$ . The continuation value to waiting is the expected value of next period's value function, conditional on the current information set  $\Omega_{it}$  and on not exploring this period:

$$V^c(n_{it}, x_{it}) = E[V(n_{i,t+1}, x_{i,t+1}) | \Omega_{it}, I_{it}^e = 0]. \quad (3)$$

Because a firm must begin exploration before the end of the five-year lease term, or else relinquish its lease, this is a finite horizon problem.

In the absence of strategic considerations, the firm owning tract  $i$  would base its exploration investment timing decision on only the exogenous variables  $x_{it}$ , which include:

estimated pre-sale value per acre, winning bid per acre, the number of years since the lease sale, a dummy for being in the last year of the lease term, the size of the tract, the year the lease was sold, firm fixed effects, area fixed effects, and year effects. To derive its dynamically optimal investment policy, it would solve a single-agent dynamic programming problem. The estimated pre-sale value and winning bid measure the firm's initial prior on the amount of reserves on the tract. The number of years since the lease sale and the dummy for being in the last year of the lease term affect a firm's decision because they measure how much longer a firm can wait to explore before it must give up its lease. The expected amount of reserves increases with tract size. The year the lease was sold controls for time-specific factors. Firm fixed effects measure firm-specific factors that affect revenues and cost. Area fixed effects measure region-specific factors such as common geological features. Year effects measure factors such as the oil price or drilling costs that may change over time.

If information and extraction externalities were present, however, then strategic considerations would become important. A firm's exploration investment decision depends on the firm's time- $t$  estimate of the quantity of reserves on its tract that it can extract, which in the presence of externalities is affected by whether or not the firm's neighbors drilled in the previous period and also by the outcome of the neighbors' drilling. A firm may be more likely to explore following a positive outcome from its neighbor, but less likely to explore following a neighbor's dry hole. As a consequence, the exploration investment decisions of the firm owning tract  $i$  would depend on the exploration investment decisions of the firms owning neighboring tracts of land. In other words, the firm owning tract  $i$  would base its investment timing decisions not only on the exogenous variables  $x_{it}$ , but also on the fraction  $n_{it}$  of neighbors  $j$  who explored at time  $t - 1$ . Each firm would then no longer solve merely a single-agent dynamic programming problem, but rather a multi-agent dynamic game.

I define a tract's "neighbors" by the following criteria. For each tract, its set of neighbors at any point in time consists of tracts nearby on which exploratory drilling could potentially have been first initiated in the previous period. In particular, a tract  $j$  is considered a

neighbor of tract  $i$  at time  $t$  if (i) it is located within a certain distance of tract  $i$ , (ii) its lease began before time  $t$ , (iii) it has not been explored before time  $t - 1$ , and (iv) it is owned by a different firm from the firm owning tract  $i$ . In most cases I also impose the additional restriction that (v) all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$ . This additional restriction enables cleaner identification because neighboring tracts each have a different value of the instrument; as a consequence, the instrument is less likely to be correlated with spatially correlated unobservables.

Measuring neighbors' effects is difficult owing to two sources of endogeneity. One source is the simultaneity of the strategic interaction: if tract  $i$  is affected by its neighbor  $j$ , then tract  $j$  is affected by its neighbor  $i$ . The other arises from spatially correlated unobservable variables (Manski, 1993; Manski, 1995; Robalino & Pfaff, 2005).<sup>4</sup> To address these endogeneity problems, I exploit a unique feature of the federal lease sales. When a tract is won, a firm must begin exploration before the end of the five-year lease term, or else relinquish the lease. As a consequence, the hazard rate of exploratory drilling has a U-shaped pattern, with high rates both at the beginning of the lease and at the end of the lease term (Hendricks & Porter, 1996). I therefore instrument for the fraction of neighbors who explore with the fraction of neighbors in the first year of their respective leases and the fraction of neighbors in the last year of their respective lease terms. The timing of a neighbor's lease term, which is related to the exogenous timing of the neighbor's sale date, is exogenous to a firm's exploratory drilling decision, as it is unlikely to have an effect except through its effect on the neighbor's exploratory drilling. Moreover, it is unlikely to be correlated with spatially correlated unobservables. The timing of lease sales is exogenous, especially for wildcat tracts, because the federal government chooses only a small subset of nominated tracts to be sold in any given lease sale (Porter, 1995); firms therefore have little influence over the timing of the lease sales. Thus, the government's choice of tracts for each

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<sup>4</sup>Simultaneity of the strategic interaction poses less of a problem because I am using the lag of the neighbors' decisions. However, if errors are serially correlated, spatially correlated unobservable variables remain a concern even with the lag specification.

sale and each tract's lease sale date are arguably random and uncertain.

To assess how a firm's exploratory drilling decision depends on the exploratory drilling decisions of its neighbors, I estimate a discrete response model by regressing the probability of exploration on tract  $i$  at time  $t$  on the fraction of neighbors  $j$  who explored at time  $t - 1$  and on other covariates  $x_{it}$ . I estimate both a linear probability model:

$$\Pr(I_{it}^e = 1) = \beta_0 n_{it} + x'_{it} \beta_1 \quad (4)$$

and a probit model:

$$\Pr(I_{it}^e = 1) = \Phi(\beta_0 n_{it} + x'_{it} \beta_1), \quad (5)$$

where  $\Pr(\cdot)$  denotes probability,  $\Phi(\cdot)$  denotes the standard normal cumulative distribution function,  $\beta_0$  is a scalar, and  $\beta_1$  is a vector of the same length as  $x_{it}$ . The coefficient of interest is the coefficient  $\beta_0$  on the fraction  $n_{it}$  of neighbors who explored at time  $t - 1$ . Both externalities suggest that firms will be more likely to drill when its neighbors are drilling as well. The information externality leads firms to drill when neighbors drill because a neighbor's drilling reveals to the firm that the neighbor thinks its tract is worth exploring, therefore suggesting that the firm's own tract may be worth exploring as well. The extraction externality leads firms to drill when neighbors drill because a firm wants to be able to extract from the common pool resource before its neighbor does. Thus, if externalities are present, we would expect  $\beta_0 > 0$ .

The instrumental variables analogs of the two models are two-stage least squares and Amemiya generalized least squares, respectively. The Amemiya generalized least squares estimator is formed by first estimating reduced-form parameters and then solving for the structural parameters; this estimator is asymptotically more efficient than a two-stage estimator (Newey, 1987).

My discrete response model of firms' exploration timing decision extends that of Hen-

dricks and Porter (1996) in two ways. First, Hendricks and Porter do not instrument for the variables they use to capture local drilling experience, and therefore do not address the endogeneity problems that arise when measuring neighbors' effects. In contrast, I instrument for the neighbors' decisions. Second, Hendricks and Porter define a "neighborhood" as one of the 51 "areas" into which the U.S. government has divided the federal lands in the Gulf of Mexico offshore of Louisiana and Texas. Using their definition, any two adjacent tracts that are located along either side of an area boundary belong to two different neighborhoods, even though they are right next to each other and may be located over a common pool of petroleum reserve. To address this problem, I define neighbors based on geographic distances, not on the arbitrary area boundaries drawn by the federal government.

### 3 Data

I use a data set on federal lease sales in the Gulf of Mexico between 1954 and 1990 compiled by Kenneth Hendricks and Robert Porter from U.S. Department of Interior data. There are three types of tracts that can be offered in an oil and gas lease sale: wildcat, drainage, and developmental. Wildcat tracts are located in regions where no exploratory drilling has occurred previously and therefore where the geology is not well known. Exploration on wildcat tracts entails searching for a new deposit. In contrast, both drainage and developmental tracts are adjacent to tracts on which deposits have already been discovered; developmental tracts, in addition, are tracts that have been previously offered in an earlier lease sale but either whose previous bids were rejected as inadequate or whose leases were relinquished because no exploratory drilling was done (Porter, 1995).

I focus my attention on wildcat tracts offshore of Louisiana and Texas that were auctioned between 1954 and 1979, inclusive. I do so for several reasons. First, my restrictions are similar to those made by Hendricks and Porter (1996), thus enabling me to best compare my results with theirs. Second, since wildcat tracts are tracts on which no exploratory

drilling has occurred previously, information externalities are likely to be most acute. Third, because the data set only contains production data up until 1990, the restriction to tracts sold before 1980 eliminates any censoring of either drilling or production.<sup>5</sup> Additional restrictions I impose for a tract to be included in my data set are that it must be a tract for which location data is available, for which the first exploration occurred neither before the sale date nor after the lease term,<sup>6</sup> and for which production did not occur before exploration.

In total, there are 2404 tracts in my data set satisfying the above criteria, from 26 different lease sales. Table 1a presents summary statistics for these tracts; Figure 1 displays the tract size distribution. The maximum tract size, as stipulated by a provision in section 8(b) of the Outer Continental Shelf Lands Act (OCSLA), 43 U.S.C. 1337(b)(1), is 5760 acres, or 3 miles by 3 miles (Marshall Rose, Minerals Management Service, personal communication, 17 April 2003). Most tracts are either 2500 acres, 5000 acres or 5760 acres in size. The average tract size is 4790 acres (s.d. = 1100) and the median tract size is 5000 acres. The average real pre-sale value (in 1982 \$) of these tracts, as estimated by the U.S. Department of Interior Minerals Management Service, is \$360 per acre, while the average winning bid is \$2520 per acre. Exploratory drilling eventually occurred on 1721 of the tracts. The U.S. government divides the federal lands in the Gulf of Mexico offshore of Louisiana and Texas into 51 areas; the data includes tracts from 26 of these areas.

For the panel data set, each time observation is a year.<sup>7</sup> Tracts enter the panel when they are sold. Tracts that were eventually explored exit the panel after the first drilling occurs. Tracts that were never explored exit the panel after five years, which is the length of the lease term a firm is given to begin exploration, or else relinquish its lease. Tracts have

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<sup>5</sup>Another reason to focus on the earlier lease sales is that post-auction lease transfers occurred less frequently in the past (Porter, 1995; John Rodi, Minerals Management Service, personal communication, 8 May 2003; Robert Porter, personal communication, 21 May 2003).

<sup>6</sup>It is possible for a lease to receive a suspension of production (SOP) or suspension of operations (SOO) which will extend the life of the lease beyond its primary term (Jane Johnson, Minerals Management Service, personal communication, October 29, 2003). Exploratory drilling first occurred after the lease term on 77 (or 3.1 %) of the 2481 wildcat tracts sold before 1980.

<sup>7</sup>As a robustness check, I also repeat my analyses on a panel in which each time period is a quarter, or 91 days.

on average 2.03 time observations in the panel. The panel spans the years 1954 to 1983.

Figure 2 plots the aggregate hazard rate of exploration. The aggregate hazard rate  $H_t$  at time  $t$  is computed as the number of tracts that explored at time  $t$  divided by the risk set  $R_t$  at time  $t$ , where the risk set is simply the set of tracts that have not explored before time  $t$ . Following Hendricks and Porter (1996), the standard deviation of the hazard is  $\sqrt{H_t(1-H_t)/R_t}$ ; the error bars in the figure indicate plus or minus one standard deviation. The aggregate hazard rate exhibits a U-shaped pattern: the hazard rate of exploration is monotonically decreasing with time except in the year right before the lease term expires, when there is a spike in exploration. It is this U-shaped feature that I exploit to construct my instruments for the neighbors' exploration decision. Since the hazard rate of exploration is high in both the first and last years of the lease term, my instruments for the fraction of neighbors who explored at any time  $t$  are the fraction of neighbors in the first year of their lease at time  $t$  and the fraction of neighbors in the last year of their lease term at time  $t$ .

Although the set of possible tracts  $i$  is limited to wildcat tracts sold before 1980 for which exploration did not occur after the lease term, the set of possible neighbors for these tracts  $i$  is larger. In particular, any tract sold between 1954 and 1983, inclusive, for which location data is available, for which the first exploration did not occur before the sale date and for which production did not occur before exploration is eligible as a potential neighbor for a tract  $i$ . Figure 3 plots the location of each of the tracts used in my reduced-form analyses.<sup>8</sup> Wildcat tracts  $i$  included in my sample are denoted with a filled circle. Other tracts that may serve as potential neighbors to these tracts are denoted with an open diamond; these tracts include drainage and developmental tracts sold between 1954 and 1983, inclusive, as well as wildcat tracts that were sold between 1980 and 1983, inclusive, and wildcat tracts that began exploration after the lease term. For a sense of the geographic span of a neighborhood, the

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<sup>8</sup>I use the latitude-longitude coordinates provided by Hendricks and Porter. The longitude and latitude are compiled from the well-bore tape as the average of the longitude (or latitude) over all wells recorded in the block for the entire coverage period of the tape. The tape includes spud dates from January 13, 1947 to July 6, 1991. This is intended to give a "representative location" of the tract. The location for blocks not on the well-bore tape was approximated by map inspection.

grey asterisk in Figure 3 denotes a wildcat tract and the circle around it encompasses all tracts located within 5 miles from it.

To be considered an actual neighbor for a given tract  $i$  at time  $t$ , a potential neighbor must also satisfy the conditions listed in the previous section: namely, that (i) it is located within a certain distance of tract  $i$ , (ii) its lease began before time  $t$ , (iii) it has not been explored before time  $t - 1$ , and (iv) it is owned by a different firm from the firm owning tract  $i$ ,<sup>9</sup> and, in most cases, (v) all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$ . In the base case, the distance used to define neighbors was 5 miles; for robustness, the analyses were also run using 4 miles, 6 miles and 10 miles.

Table 1b presents the summary statistics for variables that varied over both tract and time. Each column represents a different case. The base case is column (1). In the base case, the time period is one year in length, neighbors are located within 5 miles, and the additional restriction (v) that all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$  is imposed. There are 1139 observations in the base case. For the other cases, I vary the time period, the distance of the furthest neighbor, and whether or not all neighbors have to be sold on a different sale date. In the base case, a tract has on average 1.74 (s.d. = 1.00) neighbors at any time  $t$ .<sup>10</sup> Of its neighbors, on average 43% of them began exploration in the previous period. Moreover, during the previous period an average of 36% and 15% of a tract's neighbors were in the first and last years of their lease term, respectively.

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<sup>9</sup>For cases in which multiple firms share the lease for a tract, I define the owner of the tract as the firm with the highest share in the bid, as this firm is likely to have the primary decision-making authority.

<sup>10</sup>The base case cutoff of 5 miles was chosen so that a neighborhood would be at least as large as the size of most petroleum fields. To date, 79% and 70% of the fields spanned 3 or fewer leases for blocks with maximum water depth of 0-199 meters and 200-399 meters, respectively (Marshall Rose, Minerals Management Service, personal communication, 31 March 2005).

## 4 Results

As a benchmark, Table 2 presents the results from running the discrete response models without the use of instruments, when neighbors must be located within 5 miles of a tract. In specifications (1) and (2), the linear probability model and the probit model, respectively, are run with the base case sample in which the time period is one year in length, neighbors are located within 5 miles, and the additional restriction (v) that all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$  is imposed. For robustness, specification (3) runs the linear probability model on the sample in which restriction (v) is relaxed; specification (4) runs the linear probability model on quarterly data. The coefficient of interest is that on the fraction of neighbors who drilled at time  $t - 1$ . For all four specifications, neighbors do not have a significant effect. However, the other covariates have coefficients of the expected sign: the probability of exploring increases with the estimated pre-sale value, the winning bid and the size (acreage) of the tract. Also as expected, the probability of exploring often decreases with the number of years since the lease sale, with the coefficient being either significantly negative or insignificant at a 5% level, and increases at the last year of the lease term.

To test for the endogeneity of the neighbors' drilling, a Durbin-Wu-Hausman test is used for the linear probability model and a Smith-Blundell test is used for the probit model. Both are tests of whether the residual from a regression of the variable in question on all the exogenous variables has a significant coefficient when added to the original model; the table reports the p-value from the tests under the null hypothesis that the variable is exogenous. According to these tests, neighbors' decisions are not significantly endogenous at a 5% level in any of the four specifications. Although the tests fail to reject an exogeneity assumption, it still seems plausible, at least in theory, that neighbors' decisions are endogenous owing to simultaneity and/or spatially correlated unobservables.

To guard against any potential endogeneity of the neighbors' decisions, I instrument for the fraction of neighbors who drill with the fraction of neighbors in the first year of the lease

and the fraction of neighbors at the last year of the lease term. Table 3 presents the results from first-stage regression of the endogenous variable on the instruments and the covariates for the base case (specification (1)), as well as for three variants. The first-stage F-statistic from a joint test of the two instruments is over 10 in all specifications, so weak instruments should not be a concern (Stock & Watson, 2003). The instruments are thus correlated with the neighbors' decisions.

Table 4a presents the results from running the discrete response analysis with the use of instruments, when neighbors must be located within 5 miles of a tract. Irrespective of the probability model (linear or probit), the time period (year or quarter) and whether or not the restriction (v) that all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$  is imposed, the effect of neighbors' decisions is statistically insignificant and small: according to the results from the base case specification (1), a change in the percent of neighbors who explored in the previous period from 0 percent to 100 percent would only increase a firm's probability of exploration by a statistically insignificant 0.14. Negative effects greater than 0.15 and positive effects greater than 0.43 on a firm's probability of exploration can be rejected at a 5% level.

As with the uninstrumented regressions, the signs of the coefficients on the other covariates are as expected. According to the results from the base case specification (1), an increase in the real pre-sale value of a tract of \$10,000 per acre would increase the probability of exploration by 0.66. Thus, pre-sale values, which vary greatly from \$0 to \$18,230 per acre, have a very large and statistically significant effect on exploration decisions. Similarly, an increase in the winning bid of \$10,000 per acre would increase the probability of exploration by 0.34. Thus, winning bids, which vary from \$450 to \$60,800 per acre, have a large and statistically significant effect as well. The coefficients on the pre-sale value and on the winning bid indicate that, all else equal, tracts are more likely to be explored if their ex ante estimated values are high.

The coefficient on acreage indicates that an increase in tract size of 100 acres increases

the probability of exploration by 0.40. Thus, larger tracts are more likely to be explored. One likely explanation is that because larger tracts cover more surface area, the probability that oil and gas reserves are present is higher.

The coefficient on the dummy for being in the last year of the lease term indicates that, all else equal, a tract's probability of being explored is higher by 0.13 when it is in the last year of its lease term. This is because the option value to waiting goes to zero at the end of the lease term.

In addition to being robust to the probability model, the time period and whether or not the restriction (v) that all of tract  $i$ 's neighbors at time  $t$  must be sold on a different date from tract  $i$  is imposed, the discrete response results are also robust to the distance used to delineate neighbors; this can be readily seen in Table 4b, which compares the results from using 5 miles as the cutoff in the base case to those from using 4 miles, 6 miles and 10 miles in the linear probability model.

Externalities are likely to become more acute on smaller tracts, which are more likely to be located over a common pool of oil reserve. To examine whether strategic interactions have a larger effect on smaller tracts, where externalities arising from common-pool considerations are likely to be more prevalent, the sample is also stratified by tract size (in acres). The results are presented in Table 5. Specification (1) displays the results for larger tracts (i.e., tracts greater than or equal to 5000 acres in size); specification (2) displays the results for smaller tracts (i.e., tracts less than 5000 acres in size). As the results indicate, neighbors do not have a significant effect in either sample. Specification (3) includes a term that interacts the fraction of neighbors who drilled at time  $t - 1$  with the tract size, and is run on all tract sizes.<sup>11</sup> The coefficient on the fraction of neighbors who drilled at time  $t - 1$  and the coefficient on the interaction term are both statistically insignificant. The result that neighbors do not have a significant effect on a firm's probability of exploratory drilling is therefore robust to tract size.<sup>12</sup>

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<sup>11</sup>This interaction term is instrumented with interactions between the original instruments and acreage.

<sup>12</sup>Similar analyses were run using 2000 acres, 3000 acres and 4000 acres, respectively, as the cutoff between

Thus, regardless of whether instruments are used or not, the results of my discrete response analysis do not indicate that a firm's exploratory drilling decision depends on those of its neighbors.<sup>13</sup> Test results rejecting the endogeneity of neighbors' decisions to a firm's own decision provide further evidence that neighbors do not base their decisions on each other. My results are consistent with the weak results of Hendricks and Porter (1996): in their regressions of the probability of initial exploration, the coefficients on the variables they use to capture the neighborhood exploratory drilling experience are, for the most part, not significant. Thus, even though one may expect information externalities to be particularly acute on wildcat tracts, information and extraction externalities do not appear to induce firms to interact strategically on net.

One possible explanation why the results reject strategic, non-cooperative behavior during exploration is that firms owning neighboring tracts cooperate to jointly internalize the inefficient externalities they impose on each other, for example by forming joint ventures in exploration. Joint ventures in exploration occur less frequently than one might expect, however, because negotiations are contentious, because firms fear allegations of pre-sale anti-trust violations (Marshall Rose, Minerals Management Service, personal communication, 3 May 2005), and because prospective partners have an incentive to free ride on a firm's information gathering expenditures (Hendricks and Porter, 1992). In their theoretical model of the persuasion game, Hendricks and Kovenock (1989) find that, even with well-defined property rights, bargaining does not eliminate all the inefficiencies of decentralized drilling decisions. As a consequence, the information externality may not be fully internalized.

Following exploration, firms can cooperate by consolidating their production rights through purchase or unitization. Under a unitization agreement, a single firm is designated as the unit operator to develop the entire reservoir, while the other firms share in the

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large and small tracts. The result that the neighbors do not have an effect regardless of tract size is robust to the cutoff used to delineate tract size.

<sup>13</sup>Results from a Cox proportional hazards model without instruments also do not indicate that firms interact strategically with their neighbors. The development of an instrumental variables analog of the Cox model using nonlinear instrumental variables techniques will be the subject of future work.

profits according to negotiated formulas (Libecap & Smith, 1999b). Unitization may reduce the extraction externality. There are many obstacles to consolidation, however, including contentious negotiations, the need to determine relative or absolute tract values, information costs, and oil migration problems (Libecap & Wiggins, 1984). In addition, another free rider problem that impedes coordination is that firms may fear that if they reveal to other firms their information or expertise, for example about how to interpret seismic data, then they may lose their advantage in future auctions (Hendricks & Porter, 1996). Thus, despite various means of coordination, firms may still behave strategically and non-cooperatively, and information and extraction externalities may not be fully internalized.

A second, more likely, explanation why the results reject strategic, non-cooperative behavior during exploration is that the externalities are insignificant or even nonexistent during exploration, and do not become important until later stages of production. In her structural econometric model of the multi-stage investment timing game in petroleum production, Lin (2007) finds that while externalities from exploration have any net strategic effect, externalities from subsequent development, during which firms install production platforms, do have a net strategic effect. A firm's profits increase when its neighbor installs a production platform, perhaps because this is a signal to the firm that the neighbor's exploratory efforts were successful, and therefore that there may be deposits present.<sup>14</sup> In contrast, seeing a neighbor install a drilling rig may provide little additional information about a firm's own lease, since the drilling may or may not be successful. As a consequence, the information externality may be insignificant during exploration. Similarly, the extraction externality may not become important until firms are actually extracting oil and competing for the same resource, and therefore may also be insignificant during exploration as well.

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<sup>14</sup>The main reason the development decision is excluded from the reduced-form analysis is that, just as for exploration, a neighbor's development decision is potentially endogenous. Development is not subject to a lease term, however, and thus, unlike for exploration, the timing of the lease term could not be exploited for instruments. The design of suitable instruments for the development decisions of one's neighbors will be the subject of future work.

## 5 Conclusion

This paper examines whether strategic considerations arising from information and extraction externalities are present during petroleum exploration. In particular, it analyzes whether a firm's exploration timing decision depends on the decisions of firms owning neighboring tracts of land. A discrete response model of a firm's exploration timing decision with instruments for the decisions of its neighbors is employed.

Do the positive information externalities and negative extraction externalities have any net strategic effect that may cause petroleum production to be inefficient? The results do not indicate that externalities from exploration have any net strategic effect. A firm's exploration decision does not depend significantly on the exploration decisions of its neighbors. This is true even on smaller tracts, where strategic interactions are more likely, since smaller tracts are more likely to be located over a common pool of oil reserve. A firm's exploration decision instead depends on exogenous factors such as the estimated pre-sale value of the tract, the tract's winning bid in the lease sale, whether or not it is the last year of the lease term, and tract size.

A likely explanation why the results reject strategic, non-cooperative behavior during exploration is that the externalities are insignificant or even nonexistent during exploration, and do not become important until later stages of production. Seeing a neighbor install a drilling rig may provide little additional information about a firm's own lease, since the drilling may or may not be successful. As a consequence, the information externality may be insignificant during exploration. Similarly, the extraction externality may not become important until firms are actually extracting oil and competing for the same resource, and therefore may also be insignificant during exploration as well.

If they did occur, strategic interactions in exploration would lead to a loss in both firm profit and government royalty revenue. Since these strategic interactions would be inefficient, changes in the government offshore leasing policy would need to be considered. Possible changes include modifying the tract size, enacting policies to facilitate joint ventures

and cooperation, and selling non-contiguous tracts of land in the lease sales. The possibility of strategic interactions thus poses a concern to policy-makers and affects the optimal government policy. However, the results of the paper suggest that strategic interactions do not actually take place, at least not in exploration, and therefore that the current parameters of the government offshore leasing policy do not lead to inefficient petroleum exploration.

## References

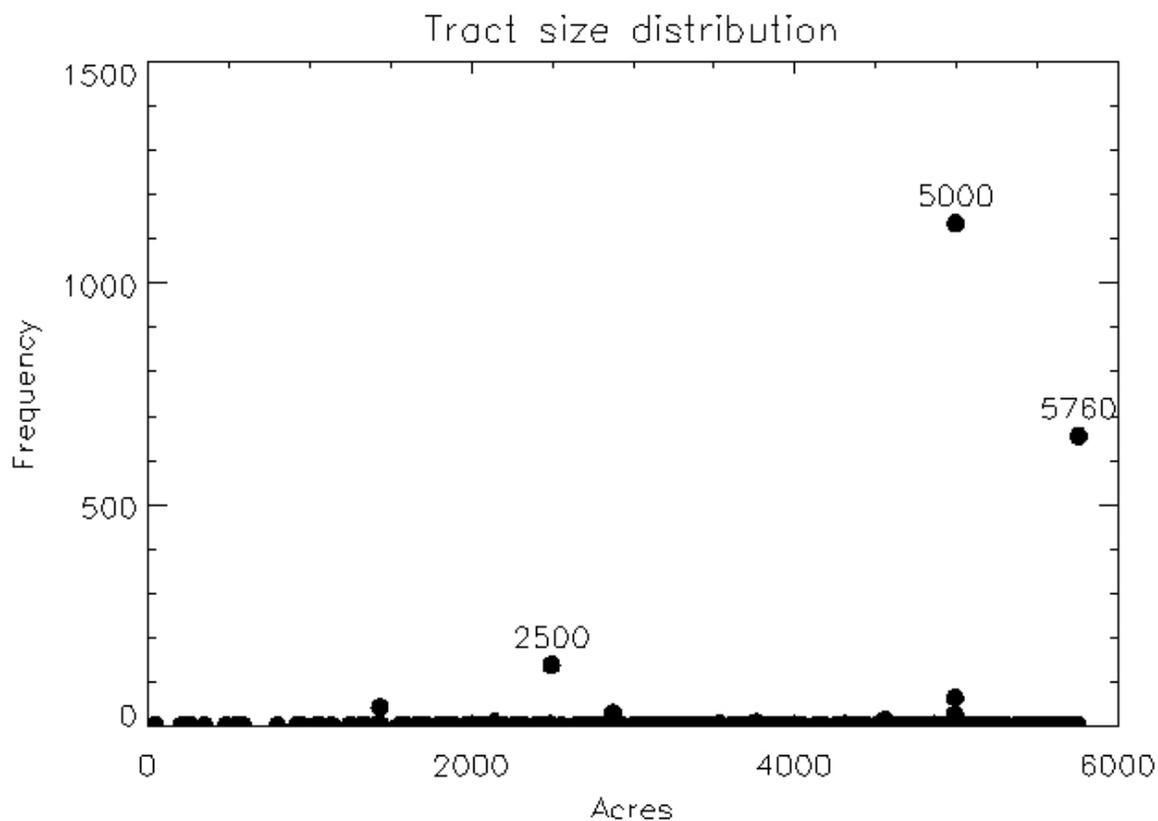
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**TABLE 1a. Summary statistics by tract**

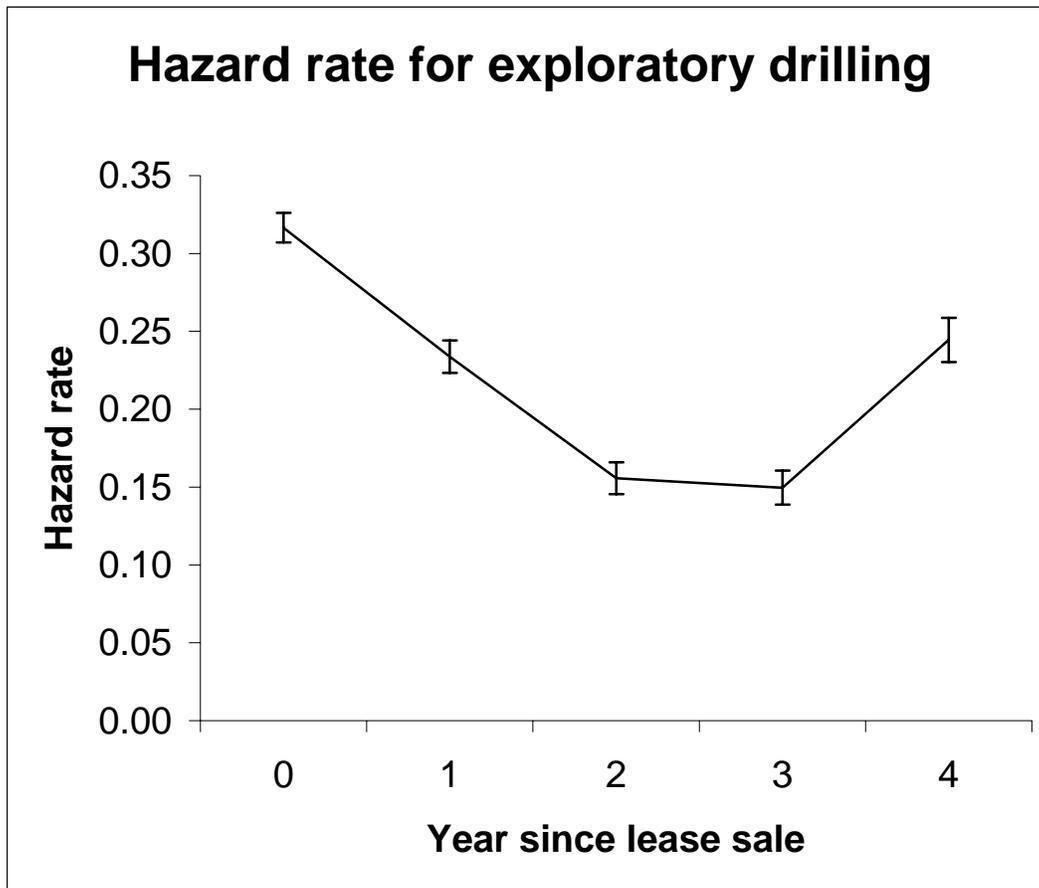
Variable	# obs	mean	s.d.	min	max
pre-sale value (thousand 1982 \$/acre)	2404	0.36	1.12	0.00	18.23
winning bid (thousand 1982 \$/acre)	2404	2.52	4.92	0.45	60.80
acreage (1000 acres)	2404	4.79	1.10	0.05	5.76
number of time observations	2404	2.03	1.73	0	4
number of years to exploration, conditional on exploring	1721	1.24	1.42	0	4

Note: The sample consists of wildcat tracts sold before 1980 whose date of first drilling did not occur after the lease term.

**FIGURE 1.**

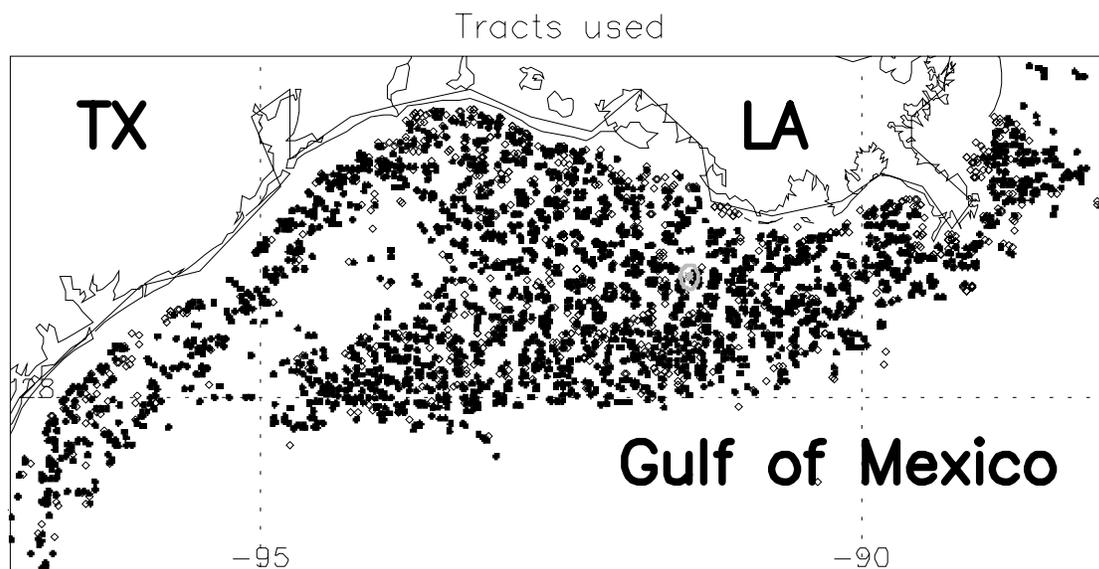
Note: The sample consists of wildcat tracts sold before 1980 whose date of first drilling did not occur after the lease term.

FIGURE 2.



Notes: The sample consists of wildcat tracts sold before 1980 whose date of first drilling did not occur after the lease term. Error bars indicate plus or minus one standard deviation.

FIGURE 3.



Notes: Filled circles denote the tracts used in the sample: these are wildcat tracts sold before 1980 whose date of first drilling did not occur after the lease term. Open diamonds denote other tracts that may be included as potential neighbors of the tracts in the sample. The grey asterisk highlights one of the wildcat tracts in the sample and the circle around it encompasses all tracts located within 5 miles of it.

**TABLE 1b. Summary statistics by tract-year**

Length of each period $t$	Summary statistics					
	year	year	year	year	year	quarter
Definition of neighbors:						
distance of furthest neighbor	5	5	4	6	10	5
neighbors have different sale date	Y	N	Y	Y	Y	Y
	(1)	(2)	(3)	(4)	(5)	(6)
dummy for exploring at time $t$	0.21 (0.41)	0.23 (0.42)	0.20 (0.40)	0.22 (0.42)	0.26 (0.44)	0.01 (0.12)
dummy for being in the last year of lease term at time $t$	0.16 (0.37)	0.13 (0.34)	0.17 (0.37)	0.16 (0.36)	0.13 (0.34)	0.12 (0.33)
# neighbors at time $t$	1.74 (1.00)	2.41 (1.61)	1.50 (0.76)	2.03 (1.33)	3.58 (2.90)	2.67 (1.97)
maximum # neighbors at time $t$	7	9	6	9	23	15
fraction of neighbors who explored at $t-1$	0.43 (0.44)	0.36 (0.39)	0.42 (0.45)	0.43 (0.42)	0.46 (0.38)	0.06 (0.19)
fraction of neighbors in the first year of lease at $t-1$	0.36 (0.45)	0.42 (0.47)	0.37 (0.46)	0.35 (0.44)	0.34 (0.42)	0.04 (0.17)
fraction of neighbors in the last year of lease term at $t-1$	0.15 (0.33)	0.13 (0.32)	0.13 (0.32)	0.14 (0.32)	0.12 (0.28)	0.04 (0.16)
# observations	1139	3932	951	1345	1854	6013

Notes: The table reports the mean for the given variables. Standard errors are in parentheses. The maximum number of neighbors at time  $t$  is simply the maximum. The sample of tracts consists of wildcat tracts sold before 1980 whose date of first drilling did not occur after the lease term. A tract-year is included for a given definition of neighbors if the tract has at least one of the designated type of neighbor at time  $t$ .

**TABLE 2. Results without instruments**

Dependent variable is probability of exploring at time $t$				
Probability model	linear	probit	linear	linear
Length of each period $t$	year	year	year	quarter
Definition of neighbors:				
distance of furthest neighbor (miles)	5	5	5	5
neighbors have different sale date	Y	Y	N	Y
	(1)	(2)	(3)	(4)
<b>fraction of neighbors who explored at <math>t-1</math></b>	0.03	0.02	0.01	-0.01
	(0.03)	(0.02)	(0.02)	(0.01)
pre-sale value (million 1982 \$/acre)	67.13 ***	34.64 **	59.19 ***	7.92 **
	(16.00)	(12.12)	(12.33)	(2.63)
winning bid (million 1982 \$/acre)	34.64 ***	27.97 ***	42.52 ***	4.63 ***
	(3.57)	(3.95)	(2.70)	(0.52)
# years since lease sale	-0.03 *	0.00	-0.02 *	0.00
	(0.01)	(0.01)	(0.01)	(0.00)
dummy for being in last year of lease term	0.14 **	0.15 **	0.16 ***	0.00
	(0.05)	(0.06)	(0.03)	(0.01)
acreage (1000 acres)	0.04 ***	0.03 **	0.05 ***	0.008 ***
	(0.01)	(0.01)	(0.01)	(0.002)
year lease was sold	0.01	0.03 ***	0.00	-0.00
	(0.01)	(0.00)	(0.00)	(0.00)
firm fixed effects	Y	Y	Y	Y
area fixed effects	Y	Y	Y	Y
year effects	Y	Y	Y	Y
p-value (Pr > F for linear; Pr > $\chi^2$ for probit)	0.000 ***	0.000 ***	0.000 ***	0.000 ***
adjusted R <sup>2</sup> (linear model) or pseudo R <sup>2</sup> (probit model)	0.22	0.31	0.16	0.04
# observations	1139	1139	3932	6013

*Test of endogeneity of fraction of neighbors who explored at time  $t-1$*

p-value	0.452	0.292	0.729	0.567
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Notes: Standard errors are in parentheses. The probit results are the change in probability for a unit change in each dependent variable; continuous variables are evaluated at their mean. To test for the endogeneity of fraction of neighbors who explored at time  $t-1$ , a Durbin-Wu-Hausman test is used for the linear probability model and a Smith-Blundell test is used for the probit model. Both are tests of whether the residual from a regression of the variable in question on all the exogenous variables has a significant coefficient when added to the original model; the table reports the p-value from the tests under the null hypothesis that the variable is exogenous. Significance codes: \* 5% level, \*\* 1% level, and \*\*\* 0.1% level.

**TABLE 3. Discrete response analysis: First-stage regressions**

Dependent variable is fraction of neighbors who explored at time $t-1$				
Length of each period $t$	year	year	quarter	year
Definition of neighbors:				
distance of furthest neighbor (miles)	5	5	5	10
neighbors have different sale date	Y	N	Y	Y
	(1)	(2)	(3)	(4)
<b>fraction of neighbors in the first year of lease at <math>t-1</math></b>	-0.20 *** (0.03)	-0.11 *** (0.02)	-0.11 *** (0.01)	-0.17 *** (0.02)
<b>fraction of neighbors in the last year of lease term at <math>t-1</math></b>	-0.09 * (0.04)	-0.03 (0.03)	-0.03 * (0.01)	-0.14 *** (0.03)
pre-sale value (million 1982 \$/acre)	2.15 (17.51)	13.64 (11.56)	-7.95 * (3.94)	0.56 (8.95)
winning bid (million 1982 \$/acre)	4.46 (3.90)	3.31 (2.53)	2.84 *** (0.78)	0.09 (2.01)
# years since lease sale	-0.034 * (0.015)	-0.05 *** (0.01)	-0.00 (0.00)	-0.00 (0.01)
dummy for being in last year of lease term	0.08 (0.05)	0.12 *** (0.03)	-0.02 (0.01)	-0.01 (0.04)
acreage (1000 acres)	0.00 (0.01)	0.02 *** (0.01)	-0.00 (0.00)	-0.00 (0.01)
year lease was sold	0.013 * (0.006)	0.01 ** (0.00)	0.00 (0.00)	0.01 ** (0.00)
firm fixed effects	Y	Y	Y	Y
area fixed effects	Y	Y	Y	Y
year effects	Y	Y	Y	Y
p-value (Pr > F)	0.000 ***	0.000 ***	0.000 ***	0.000 ***
adjusted R <sup>2</sup>	0.20	0.15	0.14	0.34
# observations	1139	3932	6013	1854
<i>Results from joint test of instruments</i>				
F-statistic	18.05	16.37	13.03	28.70
p-value (Pr > F)	0.000 ***	0.000 ***	0.000 ***	0.000 ***

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

**TABLE 4a. Results with instruments**

Dependent variable is probability of exploring at time $t$				
Probability model	linear	probit	linear	linear
Length of each period $t$	year	year	year	quarter
Definition of neighbors:				
distance of furthest neighbor (miles)	5	5	5	5
neighbors have different sale date	Y	Y	N	Y
	(1)	(2)	(3)	(4)
<b>fraction of neighbors who explored at <math>t-1</math></b>	0.14	0.19	-0.06	0.04
	(0.15)	(0.16)	(0.19)	(0.09)
pre-sale value (million 1982 \$/acre)	66.46 ***	52.90 **	60.11 ***	8.25 **
	(16.15)	(19.08)	(12.64)	(2.69)
winning bid (million 1982 \$/acre)	34.15 ***	43.04 ***	42.72 ***	4.49 ***
	(3.65)	(4.92)	(2.77)	(0.58)
# years since lease sale	-0.03	0.01	-0.02 *	0.00
	(0.01)	(0.02)	(0.01)	(0.00)
dummy for being in last year of lease term	0.13 *	0.19 *	0.16 ***	0.01
	(0.05)	(0.09)	(0.04)	(0.01)
acreage (1000 acres)	0.04 ***	0.05 **	0.05 ***	0.008 ***
	(0.01)	(0.02)	(0.01)	(0.002)
year lease was sold	0.01	0.04 ***	0.01	-0.00
	(0.01)	(0.00)	(0.01)	(0.00)
firm fixed effects	Y	Y	Y	Y
area fixed effects	Y	Y	Y	Y
year effects	Y	Y	Y	Y
p-value (Pr > F for linear; Pr > $\chi^2$ for probit)	0.000 ***	0.000 ***	0.000 ***	0.000 ***
adjusted R <sup>2</sup> (linear model) or pseudo R <sup>2</sup> (probit model)	0.21	0.26	0.15	0.03
# observations	1139	1037	3932	6013

Notes: Standard errors are in parentheses. The fraction of neighbors who explored at time  $t-1$  is instrumented with the fraction of neighbors in the first year of their lease at  $t-1$  and the fraction of neighbors in the last year of their lease term at  $t-1$ . The probit results are the change in probability for a unit change in each dependent variable; continuous variables are evaluated at their mean. Significance codes: \* 5% level, \*\* 1% level, and \*\*\* 0.1% level.

**TABLE 4b. Results with instruments, varying distance of neighbors**

Dependent variable is probability of exploring at time $t$				
Probability model	linear	linear	linear	linear
Length of each period $t$	year	year	year	year
Definition of neighbors:				
distance of furthest neighbor (miles)	5	4	6	10
neighbors have different sale date	Y	Y	Y	Y
	(1)	(5)	(6)	(7)
<b>fraction of neighbors who explored at <math>t-1</math></b>	0.14 (0.15)	0.01 (0.16)	0.04 (0.16)	0.05 (0.16)
pre-sale value (million 1982 \$/acre)	66.46 *** (16.15)	56.49 ** (18.12)	48.32 *** (13.52)	50.84 *** (11.04)
winning bid (million 1982 \$/acre)	34.15 *** (3.65)	36.56 *** (4.27)	31.29 *** (3.06)	28.94 *** (2.48)
# years since lease sale	-0.03 (0.01)	-0.03 (0.02)	-0.04 * (0.01)	-0.04 ** (0.01)
dummy for being in last year of lease term	0.13 * (0.05)	0.12 * (0.05)	0.14 ** (0.05)	0.14 ** (0.05)
acreage (1000 acres)	0.04 *** (0.01)	0.05 ** (0.01)	0.05 *** (0.01)	0.04 *** (0.01)
year lease was sold	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.00 (0.00)
firm fixed effects	Y	Y	Y	Y
area fixed effects	Y	Y	Y	Y
year effects	Y	Y	Y	Y
p-value (Pr > F)	0.000 ***	0.000 ***	0.000 ***	0.000 ***
adjusted R <sup>2</sup>	0.21	0.21	0.23	0.23
# observations	1139	951	1345	1854

Notes: Standard errors are in parentheses. The fraction of neighbors who explored at time  $t-1$  is instrumented with the fraction of neighbors in the first year of their lease at  $t-1$  and the fraction of neighbors in the last year of their lease term at  $t-1$ . Significance codes: \* 5% level, \*\* 1% level, and \*\*\* 0.1% level.

**TABLE 5. Results with instruments, by acreage**

Dependent variable is probability of exploring at time $t$			
Probability model	linear	linear	linear
Length of each period $t$	year	year	year
Definition of neighbors:			
distance of furthest neighbor (miles)	5	5	5
neighbors have different sale date	Y	Y	Y
Acreage	$\geq 5000$	$< 5000$	all
	(1)	(2)	(3)
<b>fraction of neighbors who explored at <math>t-1</math></b>	0.03	0.19	-0.01
	(0.15)	(0.28)	(0.52)
<b>fraction of neighbors who explored at <math>t-1</math> *     acreage (1000 acres)</b>			0.04
			(0.11)
pre-sale value (million 1982 \$/acre)	44.60 *	84.85 *	65.37 ***
	(18.69)	(39.53)	(16.55)
winning bid (million 1982 \$/acre)	52.76 ***	21.34 ***	34.00 ***
	(5.89)	(6.02)	(3.68)
# years since lease sale	-0.02	-0.01	-0.03
	(0.02)	(0.03)	(0.02)
dummy for being in last year of lease term	0.07	0.31 *	0.12 *
	(0.06)	(0.12)	(0.05)
acreage (1000 acres)			0.03
			(0.06)
year lease was sold	0.01	-0.00	0.01
	(0.01)	(0.01)	(0.01)
firm fixed effects	Y	Y	Y
area fixed effects	Y	Y	Y
year effects	Y	Y	Y
p-value (Pr > F)	0.000 ***	0.000 ***	0.000 ***
adjusted R <sup>2</sup>	0.25	0.18	0.20
# observations	889	250	1139

Notes: Standard errors are in parentheses. The fraction of neighbors who explored at time  $t-1$  is instrumented with the fraction of neighbors in the first year of their lease at  $t-1$  and the fraction of neighbors in the last year of their lease term at  $t-1$ . For specification (3), the interaction between the fraction of neighbors who explored at time  $t-1$  and acreage is instrumented with interactions between the above instruments and acreage. Significance codes: \* 5% level, \*\* 1% level, and \*\*\* 0.1% level.