One-to-Many Matching with Complementary Preferences: An Empirical Study of Market Power in Natural Gas Leasing[1]

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Abstract

In a two-sided market with private, multidimensional contracting, what are the costs and benefits of market concentration? I study this question in the context of firms negotiating leases for natural gas mineral rights with landowners. Firms benefit from signing geographically proximate contracts, leading to economies of density. Firms facing fewer competitors offer less desirable contracting terms to their negotiation partners. Using newly-collected data describing the location and contents of private contracts, I model firms negotiating with landowners as a one-to-many, non-transferable utility match. I extend this matching framework to allow estimating a model with complementary preferences among firms valuing sets of geographically proximate leases. The model estimates imply there are substantial benefits to market concentration that come at a cost to landowners through fewer landowner concessions. Policy simulations requiring an additional concession reveal that the gains to landowners outweigh the costs to firms, increasing average welfare by 8%.

Keywords: Market power; one-to-many matching; non-transferable utility; complementary preferences; oil and natural gas leasing; bilateral, private contracting.

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1 Introduction

What are the distributional consequences of market concentration on privately negotiated, multidimensional contracts? Whether market concentration is beneficial for producer and consumer welfare is an outstanding empirical question where, for example, producers may gain productive efficiency from market concentration and consumers may lose from monopolistic pricing. Using the oil and natural gas leasing market, I am able to measure the distributional consequences of market concentration in a setting with privately negotiated contracts (leases) and economies of density from spatial agglomeration. In the leasing market, there are quantifiable costs and benefits shared across firms and landowners who bilaterally negotiate multidimensional leases that dictate when and how an oil or natural gas well is to be drilled and how future profits are split across negotiating parties. The negotiated lease terms legally transfer mineral rights to firms, protect landowners from excessive drilling risks and disamenities, and govern how landowners share in the profits derived from their mineral estates. Using an instrumental variable model, I estimate a market power effect in private contracting whereby firms with a greater market share sign leases containing fewer landowner concessions. Using the one-to-many, non-transferable utility (NTU) matching framework, I present a model that captures both the costs of landowner protecting lease terms and benefits of spatially agglomerated lease negotiations. I extend the methodological framework by allowing spatial agglomeration to be both endogenously determined in the model and induce complementarity in firms' preferences for sets of geographically proximate leases. I then ask what happens when firms can no longer exert market power in lease terms by imposing a "price" floor, which increases firms' leasing costs. Using the estimated model, I derive a new spatial equilibrium and measure the consequent changes to firm and landowner welfare. The model predicts that leases containing more terms protecting landowners from drilling disamenities increase total welfare across firms and landowners, and I use my findings to support a more uniform leasing standard that requires landowner concessions.

This paper examines three primary questions in the context of private lease negotiations that precede oil and natural gas well development. First, does market power in private lease negotiations reduce landowner bargaining power when they sign leases that transfer their mineral rights to firms? I estimate a causal relationship between market concentration and the prevalence of landowner concessions using an instrumental variable model. I find that greater market concentration (50% leased market share) for any given firm results in leases with roughly 20% fewer landowner concessions, thereby exposing landowners to lower payoffs and more risks once firms begin drilling and extracting oil and natural gas. Second, to what extent do firms benefit from spatial agglomeration in the private market for leasing mineral rights? I build a structural model of lease negotiation to estimate the effect of spatial agglomeration, which admits estimating the effect of an endogenous market structure and facilities analyzing policy experiments that approximate new spatial equilibria. I expand the empirical one-to-many, NTU matching model by admitting that spatial agglomeration induces complementarity across proximately leased minerals. Estimation reveals that firms value spatial agglomeration in their decisions to lease individual parcels, which suggests an intrinsic value of market concentration from signing geographically proximate leases. Third, how do the equilibrium market structure and total welfare change when firms are restricted to sign more contractually binding clauses? I test the consequent changes to the equilibrium market structure and payoffs to firms and landowners from requiring more landowner concessions in each signed lease, and the results suggest an 8% total welfare gain. Measuring the relative costs and benefits of market concentration through its effect on lease outcomes and spatial agglomeration paints a more complete picture of their competing effects and the distributional consequences of these effects across the two sides of the market.

The oil and gas industry uniquely facilitates studying the competing costs and benefits of market concentration because the private contracts underpin a large and relevant industry, I observe the non-pecuniary and royalty outcomes comprising over 150,000 privately negotiated leases, spatially agglomerating leased minerals is fundamental to well development, and the counterfactual analysis evaluates potential polices that do not currently exist in practice. Fitzgerald and Rucker (2014) cite that, as of 2012, onshore oil and natural gas development comprise roughly one percent of U.S. GDP and, of that, 77% of production originates from privately owned minerals. Private ownership necessitates that firms negotiate several, if not hundreds, of private leases before drilling a single well. My data describes an urban drilling area overlaying the Barnett, tight shale formation, which is an area of significant oil and natural gas development resulting from recent technological innovation. For each lease, I quantify the specific clauses comprising the non-pecuniary, landowner concessions that result from each private negotiation. The non-pecuniary terms are matched to royalty rates, firm characteristics, geographic location of the minerals, and proximity to wells. I assembled and merged the data across three primary sources using web-scraping, text extraction, and string matching techniques, and it is currently the most comprehensive database of these private contracting terms. After using this data to estimate the structural model, the policy analyses impose that leases include more landowner concessions. The policy analyses are potentially important because they are not currently implemented in the industry[1] and represent a

[1]There are a few tangential policies. First, existing regulations stipulate that leases include surface damage clauses or have other surface protections as imposed in New Mexico, Oklahoma, North and South Dakotas, and Montana. The jurisdiction of leases mimics that of some local ordinances; however, since spring of 2014, Texas passed HB40 that limits the efficacy of ordinances passed under "home rule" significantly.

low cost mechanism to increase protection of landowners and property values during and following drilling activity.[2] Further, the benefits accrued from more restrictive contracting spillover to nearby, non-negotiating landowners,[3] and I estimate that firms continue to profit from lease market agglomeration.

I begin by estimating an instrumental variable model that quantifies the causal relationship between firms' market shares of signed leases and lease outcomes, like royalties, term lengths, and the prevalence of specific legal and drilling restrictions. The estimates reveal a consistent negative relationship whereby firms with more market power sign leases containing fewer landowner concessions. The model controls for endogeneity between market concentration and lease outcomes by instrumenting market concentration with measures of firms' nearby, pre-2004 well production activity and their regulatory prowess. The instruments are related to firms' market concentrations through drilling and regulatory experience; however, they represent a shift in technology that altered where and how the industry leased minerals pre- and post-2004. Technological innovation, after 2004, allowed firms to profit from leasing minerals with urban and suburban households and drilling wells in densely populated regions overlaying tight-shale formations. The empirical results suggest that a market share of 50% results in that firm signing leases containing around 20% fewer clauses. Leases that contain fewer landowner concessions reduce the firms' costs of drilling and exploration while it increases landowners' exposure to drilling risks.[4]

To quantify the how the costs and benefits of market concentration are shared across firms and landowners, I estimate a two-sided, one-to-many matching model that assumes non-transferable utility (NTU) whereby a single firm signs sets of many leases owned by individual landowners. In the data, I observe the final contracting outcomes describing which firms sign leases with specific landowners and their location, firm and landowner attributes, and the final contract contents, including royalties and specific legal terms written into each lease. The one-to-many, NTU matching framework allows me to estimate separate and heterogeneous preferences over pecuniary and non-pecuniary lease terms for both firms

[2]There is a growing literature capturing the hedonic value of proximity to drilling activity in the environmental economics literature. Existing literature finds that households internalize perceived risks of nearby drilling activity through decreased property values (Muehlenbachs, Spiller, and Timmins (2015), Gopalakrishnan and Klaiber (2014), James and James (2014), Boxall, Chan, and McMillan (2005)), and a growing health literature finds that proximity to drilling is correlated with incidence of infant birth weight (Hill (2013)) and harm to drinking water (Hill and Ma (2017), Vengosh, Jackson, Warner, Darrah, and Kondash (2014)).

[3]There are subsets of clauses that benefit nearby, non-negotiating landowners who may experience negative drilling externalities without financial remuneration because their property is located far enough away from the physical well (and wellbore).

[4]Other work by Timmins and Vissing (2015) quantifies a relationship between lease clauses and future drilling violations, which suggests that more landowner concessions act as a deterrent for future violations and are a potential substitute for local ordinances, or lack thereof.

and landowners that arise from bilateral decision-making.[5] The NTU assumption does not obviate transfers, but rather assumes they are determined before firms and landowners decide to sign a lease, and the modeling framework allows me to model the separate components of these multidimensional contracts. Further, firms' and landowners' choices describing with whom to sign a lease are not observed, and leases signed by any given pair depend on the preferences of all firms and landowners in the market, a feature that allows the matching model to more accurately mimic negotiations as they occur in the industry.[6]

I extend the one-to-many, NTU matching framework by estimating a model with a match externality[7] that measures the endogenously determined market structure and by allowing the match externality to induce complementary preferences for geographically proximate leases. Market structure is modeled as the share of leases signed by a single firm in a geographic region[8] and enters firms' valuation of each potential landowner match. Consequently, firm's increasing market share in a particular region increases the value of the remaining, unsigned leases in that market, inducing a complementary relationship across geographically proximate parcels of land. To my knowledge, this is the first paper to estimate a large-scale model with a match externality inducing complementary preferences within the one-to-many, NTU framework.[9]

Estimating a NTU, one-to-many matching model in which firms directly value market structure is a complicated empirical problem in terms of equilibrium existence, multiplicity, and stability, and the following summarizes the main assumptions used to increase the model's computational tractability. The proposed model is predicated on the observed leasing market having low frictions and satisfying a pairwise stable equilibrium. Pairwise stability imposes that there is not a firm and landowner pair preferring to sign a lease with one another more than their current lease given a fixed market structure and set of lease terms. Explicitly modeling firms' values of spatial agglomeration implies that any deviating pair

[5]Assuming NTU, the model is estimated using two exogenously given utility functions that describe firms' and landowners' preferences separately. Compared to a more traditional discrete choice setting, both sides of the market have autonomy to reject any given firm and landowner pairing.

[6]A firm may sign a lease with their most preferred landowner, or they may sign a lease with a landowner lower in their preference ranking because their most preferred received a strictly better offer from their competitor. Matching models have endogenous choice sets whereby each matched pair depends on the preferences of all players on both sides of the market.

[7]A match externality refers to a situation where one or both sides of the markets' values reflect the total assignment of the market.

[8]Measuring market structure as a density of the firms' geographically concentrated leasing efforts follows from the industrial organization literature studying chain store entry patterns as in Jia (2008), Holmes (2011), Ellickson, Houghton, and Timmins (2013), and Nishida (2014).

[9]Uetake and Watanabe (2013) estimates a one-to-one NTU match with an externality inducing substitutable preferences; Fox and Bajari (2013) estimates a one-to-many, transferable utility (TU) match with complements.

must consider, not only their own sets of outside options, but also all other agents' responses to their deviation since firms' values are a function of the total market assignment.[10] Without restricting firms' beliefs about their competitors' actions, firms and landowners may not be able to achieve a stable, pairwise equilibrium in the lease market. Assuming that firms have myopic beliefs about their competitors' leasing behaviors, I estimate a model in which the fixed, total market assignment used to find the pairwise stable equilibrium is approximated through a Myopic Estimation Function.[11] Under myopia, firms believe that other active firms will sign the same number of leases as observed in the data with no restrictions to the specific leases their competitors sign. An equilibrium selection mechanism assuming that firms extend lease offers to landowners mitigates multiplicity and mimics industry behavior, and the equilibrium implied by the estimated parameters is verified post-estimation.

Estimates from the matching model reveal that firms value signing spatially concentrated leases and, consequently, individual parcels more when they lease a large share of that market. Second, the model captures firms' costs of landowner concessions along with the added value of those concessions for landowners. Combined with the estimates from the instrumental variable models, the estimates suggest that firms benefit from market concentration along two dimensions. With greater concentration, firms sign leases containing fewer landowner concessions and they derive value from spatial agglomeration, thereby reducing firms' contracting and compliance costs and increasing landowners' risks. While agglomeration benefits firms and landowners, fewer landowner concessions cause more harm to landowners in the long run. The proposed policy experiments capture firms' responses when leases are restricted to be more uniform and contain additional clauses protecting landowners. Policy experiments suggest that requiring a single, additional clause increases the average welfare from contracting by 8%, and the gains are distributed more evenly across landowners, while the costs to firms are a fraction of the costs to implement the most restrictive policy. The counterfactual results suggest that higher contracting costs benefit landowners enough to compensate firms' losses, and firms gain value from more spatially concentrated leasing effort. Further, better contracting protects landowners' non-negotiating neighbors from future negative drilling externalities, which is an added external benefit to the policies.[12]

[10]NTU matching models without externalities require deviating pairs only consider their own set of potential matches because their match values are only a function of the observable match attributes and not the total market assignment.

[11]Described in greater detail in Section 4.2, this assumption follows the empirical examples set by Uetake and Watanabe (2013) and Baccara, İmrohoroğlu, Wilson, and Yariv (2012).

[12]The presented welfare measures try to capture the public benefits received by landowners no longer signing leases in the counterfactual scenarios. Also, I cannot say definitively whether firms would compensate required landowner concessions with worse lease terms on other dimensions. However, lease attribute summary statistics presented later in the paper reveal that good leases are more often good leases for landowners on all dimensions.

The paper contributes to the empirical matching literature by adding a match externality inducing complementary preference to the one-to-many, NTU matching framework and applying the method to a new industry, the oil and natural gas lease market. The empirical techniques build on the work of Uetake and Watanabe (2013), Agarwal (2015), and Boyd, Lankford, Loeb, and Wyckoff (2013). Uetake and Watanabe (2013) set-estimates a one-to-one, NTU match with a match externality that induces substitutable preferences. Substitutable preferences ensure equilibrium existence and that the set of preferences form a lattice, which allows them to use theory by Hatfield and Milgrom (2005) to inform their estimation technique. Agarwal (2015) estimates a one-to-many, NTU model of hospitals matching to residents, and the specified vertical preferences over resident characteristics ensures there is a unique, pairwise stable equilibrium.[13] Boyd, Lankford, Loeb, and Wyckoff (2013) estimates a one-to-many match between teachers and schools based on sorting patterns and by imposing that schools always extend offers to teachers.

The paper builds on a small one-to-many, NTU empirical literature and studies a problem largely tackled in the theory literature. This literature has evolved from "matching with couples" with strong restrictions regarding the effect that couples can have on the total match.[14] Other studies have focused on markets in which agents are able to observe all interactions attributed to potential deviating pairs in order to sustain an equilibrium (Sasaki and Toda (1996) and Hafalir (2008)). A more recent approach to characterizing equilibrium under complex preferences is to study matching in large market settings as demonstrated by Kojima, Pathak, and Roth (2013), Azevedo and Hatfield (2012), and Che, Kim, and Kojima (2014).

In general, a NTU, one-to-many matching with a match externality (taking the form of market shares) inducing complementary preferences can be useful for studying other markets. The model is adaptable to labor markets where firms search for a diverse workforce and it is important to amass shares of workers performing different, complementary tasks. Similarly, students may benefit from learning alongside peers with diverse backgrounds or varying skill levels. Schools, students, and teachers may value classrooms comprised of a mixture of students from different socioeconomic backgrounds, of varying academic achievement levels, or with varying interests, which may induce complementary preferences represented by shares of students with diverse backgrounds or skills.

[13] Agarwal and Diamond (2014) demonstrate the value of using the "many" component of one-to-many matches to identify vertical preferences when matches are not perfectly assortative, and it informs the estimation strategy in Agarwal (2015).

[14] The number of couples may be small relative to the size of the market (Kojima, Pathak, and Roth (2013)) or the existence of couples cannot engender cycles (Ashlagi, Braverman, and Hassidim (2014)), and this literature is surveyed in Biró and Klijn (2013).

Topically, this paper studies the private natural gas leasing market and contributes to the growing literature in environmental and energy economics characterizing the industry and its implications. The contribution to the literature is twofold since it is the first paper to model the bilateral, private negotiations between firms and landowners using a method that allows for autonomy on both sides of the market, and to estimate the value of spatial agglomeration in the private leasing market. Prior work on leasing focuses on state and federally owned land whereby mineral rights are auctioned, which includes Libecap and Wiggins (1985), Porter (1995), Hendricks, Pinkse, and Porter (2003), Fitzgerald (2010), and Lewis (2015), among others. Holmes, Seo, and Shapiro (2015) study the sequence of firm decisions moving from leasing to production in a theoretical model, and Timmins and Vissing (2015) study the heterogeneous distribution of protective leases across households using an environmental justice argument.

Section 2 describes the institutional details and data description. Section 3 proposes a model of lease quality that tests whether firms exert market power in pecuniary and non-pecuniary, privately negotiated contracting terms. Section 4 describes oil and natural gas lease negotiations in the context of a one-to-many, empirical matching framework that assumes non-transferrable utility, which is followed by Section 5 detailing how I estimate the proposed structural model. Sections 6 and 7 report estimates from the IV and matching models, respectively. Section 8 describes a counterfactual analysis using the estimated models, and section 9 concludes. Additional model, estimation, simulation, robustness check, counterfactual, and data details can be found in the Appendix.

2 Institutional Details & Data

2.1 Technology: Hydraulic fracturing

It is reported that the supply of shale gas to total US natural gas production jumped from 1.6 percent in 2000 to 23.1 percent by 2010 with increasing projections (Richardson, Gottlieb, Krupnick, and Wiseman (2013)). Technological innovation in the oil and natural gas industry has increased access to reserves trapped in tight-shale formations like the Barnett Shale underlying Tarrant County, Texas, the area of study. The combination of large-scale hydraulic fracturing,[15] horizontal drilling techniques, and more precise 3-D seismic surveying techniques have unleashed access to otherwise unattainable resources with increased efficiency.

[15] Hydraulic fracturing techniques have been in active use since the 1950s, and before the formal process developed, well operators used other artificial forms of stimulation to extract oil and gas (Zeik (2009)).

Hydraulic fracturing involves injecting fluids, primarily water mixed with other chemicals, at high pressures into the drilled well such that the shale cracks and produces artificial fissures throughout the strata. The fracturing fluid contains proppants, like quartz sand grains, that are deposited into the fissures and prop them open well after the pressure is released and fracturing fluid returns to the wellhead. The propped fissures allow oil and natural gas to flow freely to the wellhead in commercially producing quantities. Horizontal drilling techniques, with laterals measuring roughly 3000 to 5000 feet, ensure that large quantities of shale are exposed to the hydraulic fracturing stimulation while boring fewer holes into into the ground (Zeik (2009); King (2011)). Further, the fracturing stages can take place iteratively or all at once, potentially allowing the firm more freedom to pace natural gas extraction with other operation decisions or market conditions.

2.2 Regulatory Structure

The oil and natural gas industry is regulated at federal, state, and local levels of government although regulation has historically been done mostly by the states. The state of Texas has a long history of conventional well development reaching back to 1866 when the first well was drilled in Nacogdoches County, Texas,[16] the Texas Railroad Commission (TRC) has regulated the oil and gas industry since 1917. The TRC has jurisdiction over the "exploration, production, and transportation of oil and gas prior to refining or end use,"[17] and they exercise their jurisdiction by enforcing rules written in Chapter 3 of the Texas Administrative Code (2015b). States regulate well location and spacing, drilling methods and requirements, plugging and disposal methods, and site restoration (Richardson, Gottlieb, Krupnick, and Wiseman (2013)). The federal government protects air and surface water quality, and endangered species. Municipalities may also exercise jurisdiction over industry operations by passing local ordinances.

Before a well is drilled, oil and gas firms must own the rights to all minerals from which they want to extract, and the surface area must be large enough that a well can be positioned far enough away from any existing infrastructure or unleased property.[18] Beyond satisfying such well spacing and density requirements and meeting a minimum royalty standard of $\frac{1}{8}$-th in Texas,[19] the lease phase is largely unregulated. The negotiated leases act as supplementary

[16] http://texasalmanac.com/topics/business/history-oil-discoveries-texas.

[17] Natural Resources Code (2015a) Section 91.101-.1011

[18] Such regulation is designed to increase the efficient extraction of oil and natural gas without over drilling and to protect the correlative rights of landowners, even when landowners' properties are too small to support drilling a single well. Current research evaluates the efficacy of these well spacing, density, and unitization policies.

[19] The TRC requires royalty rates of at least one eighth of the gross production of gas (Natural Resources Code (2015a), Sec. 32.1072). In addition, there are rules that establish payment windows during production

regulatory mechanisms, protecting landowners' properties and aesthetics and mitigating their exposure to drilling disamenities during the well development phases. The TRC does not regulate aspects of the drilling process like excessive noise and traffic, legal aspects of mineral ownership and transference, and use of certain equipment (e.g. compression stations). They do not require pre- water and soil testing[20] and impose lax proximity restrictions.[21] While there are some local ordinances targeted to these issues, the rules are heterogeneous across space and do not protect all landowners. As a consequence, landowners may negotiate leases with added concessions that restrict firm behavior on these dimensions.

Much of the legal literature focuses on potential state and federal regulations to curb the environmental risks incurred by unconventional drilling techniques like hydraulic fracturing (Olmstead and Richardson (2014); Konschnik and Boling (2014)). Richardson, Gottlieb, Krupnick, and Wiseman (2013) explores the existing state of heterogeneous regulatory standards across states. I am interested in quantifying the firms' costs and landowners' benefits derived from landowner concessions by modeling private lease negotiations in Tarrant County and, subsequently, using the model to approximate the market response to policies that require more landowner concessions. Additional legal and institutional leasing details can be found in Timmins and Vissing (2015).

2.3 Data

The estimated models rely on data that describe leases negotiated between firms and landowners that temporarily transfer the rights of the mineral estate to firms for the purpose of oil and natural gas exploration and extraction. My sample spans leases signed in Tarrant County, Texas between 2003 and 2013 with the majority signed beginning in 2006 as a consequence of technological innovation and the resulting "shale revolution." Three primary sources of data are used in the analysis: multidimensional lease data describing the specific pecuniary and non-pecuniary terms of the contracts; well permitting and production data that describes firms' operating activities; and housing data describing where each lease is signed and the parcel (land) attributes. The data set is constructed at the parcel level, which requires matching each lease document to a parcel using string matches based on addresses and buyer/seller/owner names. With the precise location of each signed lease, they are mapped to nearest well and other geographic identifiers used in the empirical analysis. In the following sub-sections, I describe the primary data sources and refer readers to the

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and reporting requirements (Natural Resources Code (2015a), Sec. 91.401).

[20]In other states, firms require pre-drilling water testing of sources located within a distance buffer of the proposed well.

[21]In Texas, the set-back 200 feet but there is no restriction for proximity to water sources

Appendix for more detailed data collection and assembly descriptions.

2.3.1 Lease Data

Leases are publicly (and digitally) available documents filed with the county clerk offices, and each lease is comprised of primary and auxiliary clauses. Primary clauses exist in all contracts and consist of royalty rates, or the fraction owed to the landowner once a well begins selling natural gas extracted from their mineral estate, term length, or the period of time a firm has to drill a well before the rights to the mineral estate are relinquished to the landowner, and bonuses, or fixed payments owed to landowners when the lease is signed. Table 1a summarizes the primary terms.

Auxiliary clauses are elements of the contracts that are in addition to the more standard leasing form used in the industry and may require environmental testing, limits to noise and traffic from drilling activity, restrict which chemicals can be used to fracture a well, and clearly delineated legal responsibilities across grantors and grantees, among other concession types. Auxiliary clause data originates from two sources: the "Drilling Down" series (Urbina (2011)) published by the *New York Times* and the Tarrant County Clerk's office. Pdf files were converted to text files that were then text-mined for instances of specific language describing many types of clauses that can be negotiated into leases. Table 1b summarizes the auxiliary clauses in the data and how specific clauses are categorized into types of landowner concessions. Table 1b also reports the frequency (of 150,501 total leases used in the analysis) of specific landowner concessions like requisite *Environmental* testing (0.177) or restrictions to *Residential Streets* (0.092). The individual clauses are categorized into clause types like those restricting *Disamenities* experienced during drilling and production, or added *Aesthetic*, *Legal*, *Water* protections. For each clause type, I sum the count of clauses included in each lease and divide by the total, so a lease comprised of additional *Environmental* testing and *Noise* and *Freshwater* restrictions is assigned $\frac{3}{5}$ for the *Disamenity Bundle*. The primary analysis focuses on clause types; however, the Appendix reports estimates using individual clauses, and one may refer to the Appendix for a more thorough discussion of clause types.

Because the bonus sample is small at roughly two percent of the total lease sample size,[22] analyses explicitly incorporating the bonus payments are reported in the Appendix.[23] Table 1c describes the raw correlations across the dimensions of lease quality. Without controlling for any other observable characteristics, Table 1c describes a world in which features of the contracts are positively correlated.[24] The positive correlations suggest that a good lease for

[22] Most of those leases were signed in 2008 predominantly by nine firms. Firms and landowners are not required to report bonuses with the Tarrant County Clerk office.

[23] Section 4 describes how bonuses enter the one-to-many, NTU match used to model the lease negotiations.

[24] Longer term lengths are interpreted as less beneficial for landowners because they cannot sign leases

landowners is good in all dimensions, and landowners are not necessarily compensating fewer clauses with higher royalty rates or bonus payments, for example.

2.3.2 Housing Data

The Tarrant County appraiser's office supplied map files of all parcels in the county along with files delimiting city, subdivision, water source, and abstract boundaries.[25] Further, they supplied appraisal and the available reported sale values[26] for each property type going back to 2008, a data set that also includes house and property characteristics like parcel and house size, and room counts, among other descriptive characteristics. The analysis focuses on single-family, residential properties, and Table 2b describes the parcel characteristics in the data. The match between houses (or parcels) and leases allows for a more precise definition of the lease location and, consequently, proximity to firms' existing infrastructure. Further, precise lease locations allow me to group the leases into clusters assigned to specific wells and wellpads that extract natural gas from the leased mineral estates.

2.3.3 Well Data

Publicly available data describes every permitted and producing well in the state of Texas, along with monthly well production values, and this data can be accessed through both Drilling Info and the Texas Railroad Commission (TRC).[27] Each well observation includes important dates like the date the permit was issued by the TRC, and the spud, completion, and first production dates. The data also report the operator of the well, permitted acreage, and lateral depths and lengths, among other well characteristics. Often several wells will be drilled in close proximity, which is classified as a wellpad, and I identify wellpads by grouping wells drilled within 63 meters of one another.

Each well is geographically identified and mapped to leasing activity using the minimum distance between leased parcels and wells.[28] Table 2b describes proximity between leased parcels and the nearest well and pipeline using the TRC's well and pipeline data. Other firm-specific drilling activity measures are described in Table 2a including whether the firm is a landman or operator, the count of wells drilled before 2004 (pre-"shale revolution"), forced

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with other firms or re-purpose the minerals until the primary term expires. A negative correlation between term length and (1) royalty and (2) clause quality suggests the lease is preferred by landowners.

[25] `http://www.tad.org/gis-data`.

[26] Texas is a non-disclosure state, so sale values are not required to be reported.

[27] My access to Drilling Info is through the Duke University Energy Initiative and TRC data is accessible through their website, `http://www.rrc.state.tx.us/`.

[28] I use lease and production dates to check for inconsistencies like leases signed after a well is drilled and producing oil and natural gas.

pooling and field rule applications to the TRC. Firm complaints are also collected from the TRC, and finally, I report summaries of 18-month future oil and natural gas prices and volatility measures based on the Texas Henry Hub delivery date and reported by Bloomberg.

3 Market Power & Lease Quality

Do firms exercise market power through privately negotiated leases by signing contracts that contain fewer landowner concessions? I present an instrumental variable model relating multi-dimensional lease quality to market concentration that is designed to answer this question. The models use data describing the legal and environmental clauses comprising natural gas leases signed in Tarrant County, overlaying the Barnett, tight-shale formation. The following sections describe the model and identification strategy used to test whether firms exert market power on privately negotiated contract outcomes in the lease market.

3.1 Model

Whether market concentration leads to market power in privately negotiated contract terms is an empirical question. The oil and natural gas lease market is comprised of landowners $i \in \mathcal{N}$ signing leases with firms $j \in \mathcal{J}$ that contain legal terms θ_{ij} dictating how firms behave during the drilling, producing, and plugging phases of well development, which includes the process of hydraulic fracturing in tight-shale regions like Tarrant County. Terms may stipulate additional environmental testing, limits to operating noise and traffic, and restrictions to surface access, among other legal clauses described in greater detail in Section 2.3 and the Appendix. Amassing the mineral rights to geographically concentrated parcels of land is intrinsic to the regulatory framework that requires firms own the rights to the large, contiguous mineral acreage from which they want to extract.[29] Consequently, firms value signing leases with landowners owning property in regions where they have already amassed the legal rights to a large acreage, increasing the incremental value of each newly signed lease as firms converge to the required acreage to drill a new well. Under positive assortativity, the relationship between land leasing and satisfying well permit regulations suggests that the value of each subsequent negotiation is increasing in market share as described by the inequalities in (1). Landowners owning property that is more valuable to a firm through spatial agglomeration are offered leases with more landowner concessions designed to attract

[29] Well spacing and density regulations further stipulate that new wells must be located a minimum distance from existing wells and unleased mineral rights, as noted specifically in the Texas Administrative Code (2015b) and common to state regulators overseeing active oil and natural gas industries.

the firm's most valuable landowners.[30]

$$\theta_{ij}(share_j) \geq \theta_{ij}(share'_j) \text{ if } share_j \geq share'_j \tag{1}$$

Conversely, as firms amass market concentration, there are fewer competing firms vying for rivalrous property rights that may cause the dominant firms to offer less desirable contracting terms. Estimating a relationship between market concentration and the contractually negotiated outcomes reveals which of the competing incentives prevails in the private lease market.

The lease quality model relates the pecuniary and non-pecuniary contract outcomes, θ_{ij}, to measures of market structure ($share_j^m$) and other observable characteristics ($q(X_i, Z_j; \delta)$) as described by Equation (2). Estimating a negative effect of market concentration, $\gamma < 0$, in (2) for different measures of θ_{ij} reveals that firms exercise market power in the lease market by signing leases that contain fewer landowner concessions protecting landowners from drilling disamenities.

$$\theta_{ij} = q(X_i, Z_j; \delta) + \gamma share_j^m + \epsilon_{ij} \tag{2}$$

The empirical model is estimated for many different measures lease quality, like royalty, term length, and landowner concession clauses, that quantify the multidimensionality of the oil and natural gas contracts. The following section describes the potential endogeneity between market structure and contract outcomes and the instruments proposed to break the endogeneity.

3.2 Identification

Instrumental variables are used to mitigate omitted variable bias, breaking potential endogeneity between market structure and lease outcomes, like royalty, term length, and landowner concession clauses, in a setting where the direction of the bias is uncertain. Many firms may concentrate their leasing efforts in regions with higher expected natural gas production, thereby decreasing total market concentration, and as a consequence, offer leasing contracts containing more landowner concessions that attract signatories. Conversely, markets may have more active property rights attorneys or neighborhood coalitions that jointly

[30]Holding the parcel's other observable characteristics constant, a firm derives more value from signing a lease in a market where that firm's market share is greater. Because firms value that parcel more than similar parcels located in markets where they have a lower market share, I assume that firms extend more desirable offers to the landowner to induce them to sign over a competitor's offer. If the offer is not large enough, the firm increases the risk that the landowner signs a lease with their competitor.

negotiate leases, which may drive up the landowner concessions written into leases signed in that market. The same regional characteristics may deter firms from signing leases in that market, increase market concentration, and allow firms to exercise market power by offering leases that contain fewer landowner concessions. Consequently, it is difficult to predict the direction of the bias engendered by omitted variables.

I propose two instrumental variables that measure firms' pre-2004 drilling activity in nearby markets and their regulatory prowess exhibited by forced pooling approvals from the Texas Railroad Commission (TRC).[31] Drilling in Tarrant County before 2004 was isolated to the rural, northwest corner of the county, though much of the county is urban or suburban. Technological innovation that combined large-scale hydraulic fracturing capable of penetrating tight-shale formations with long, horizontal laterals freed firms to lease and drill in densely populated regions. Privately owned minerals located in urban regions present new challenges to firms as they must negotiate more individual leases and form irregular drilling units dictated by urban and suburban neighborhood characteristics. Further, drilling disamenities implicate more, tightly spaced households that alter the contents of negotiated contracts compared to rural.[32] The instruments hinge on technological changes that alter the industry and drilling strategies before and after 2004 and across rural and urban landscapes. Firms with past drilling and regulatory experience can knowledgeably amass the mineral rights to large, contiguous acreage in an urban setting, while not necessarily benefiting from that same experience when negotiating specific contracting terms in the new, urban setting. Descriptions of the instruments and threats to identification follow.

Pre-2004, nearby drilling activity is measured by the count of firms' wells drilled in nearby, geographic markets before 2004, years pre-dating leasing activity associated with the shale revolution that occurred in Tarrant County and across the United States. Identification holds if pre-2004, nearby spatial drilling behavior is uncorrelated with post-2004 contracting behavior, whereby 2004/2005 marks the described change in industry technology. The assumption is violated if there is spatial correlation between pre-2004 producing wells and current contracting behavior, whereby areas with high expected production attract more firms and consequently elicit more competitive contracting terms (i.e. more landowner concessions). Research by authors like Hendricks and Porter (1996) and Levitt (2009) explore how firms use experience and information spillovers from geographically proximate oil

[31] The Appendix presents a series of robustness checks including similar results that use other instruments that use the pre-2004, nearby well activity and pre-2004 Texas-wide drilling activity. Further, the results are robust to other measures of regulatory prowess like special field rules or required reimbursements from negligent plugging of old wells, for example, though these results are not reported.

[32] Urban households may disallow firms to access the minerals by drilling on their property, whereas rural landowners leasing a large acreage may request firms locate wells on an isolated part of their property.

wells to inform their drilling decisions. However, pre-2004 drilling in Tarrant County was restricted to rural regions, and new technology opened firms to lease and drill profitably over much of Tarrant County even though firms may have initially started signing leases nearer to the rural region, which engenders the desired relationship between pre-2004 drilling activity and present spatial concentration. Further, the observed leases are signed at least one to two kilometers away from pre-2004 drilling activity[33] and, on average, at least three years after. In Texas, firms are required to report monthly well production to the TRC, and production values are then open to the public, suggesting that firms are not able to act on private, spatially proximate well production. Finally, firms that are more active in earlier periods, like Mitchell and Devon, are not necessarily the most active in later periods suggesting broader changes to market structure and participation pre- and post-shale revolution.

Second, I use firms' regulatory prowess at forming drilling units to instrument for market structure. Because Tarrant County is densely populated, firms with experience leasing and drilling in densely populated regions are at an advantage amassing leased market share there. Regulatory prowess is measured using counts of firms' approved applications to the TRC to force pool drilling units[34] across Texas. Forced pooling is particularly difficult to invoke in Texas where regulators want to ensure all landowners have the opportunity to voluntarily sign leases and profitably extract their minerals, even when the parcel size is small. Voluntary agreement across more landowners (to drill a single well) in an urban setting is difficult, engendering a negative relationship between forced pooling experience and market concentration in Tarrant County, specifically. The instrument is invalid if past approvals across all of Texas are correlated with the specific contracting terms written into privately negotiated leases in Tarrant County. There may be a positive correlation if the regulatory experience is similar to a specific clause, and though there are lease terms that address pooling restrictions specifically, they are not included in the analysis because they follow a uniform industry standard.[35] Largely, leases are negotiated on dimensions not related to pooling, and the specific clauses analyzed in this paper address environmental standards, royalties, and matters regarding liability.

[33] The IV strategy that uses an instrument describing nearby behavior is similar to that proposed in Hausman (1996) using nearby market prices, when controlling for market (and brand) fixed effects, to instrument for own market prices, which are assumed independent of stochastic disturbances in demand.

[34] Forced pooling is a tactic used by firms to gain access to minerals owned by landowners refusing to sign leases or that cannot be located due to severed minerals, for example, or minerals owned by individuals that do not own the rights to the surface estate.

[35] Most leases in Tarrant County include a pooling clause as a part of the standard lease. The pooling clause limits the size of the total pooled acreage for a future drilling unit, and it grants the firms the right to pool individual parcels. Such clauses are necessary in Tarrant, especially, to ensure the value of mineral rights are not diluted and that firms are able to drill a single well to access minerals located beneath many small plots of land.

The instrumental variable model estimates the causal relationship between market concentration and pecuniary and non-pecuniary contract terms and is a framework to test whether firms exert market power. Each model is estimated with year-level fixed effects that control for market-wide, unobserved shocks and inference controls for unobserved spatial correlation by estimating spatially clustered standard errors. Section 4 describes a model of spatial agglomeration that attempts to parameterize how the market structure is formed by modeling firms' preferences for spatial agglomeration in the context of signing leases with landowners across Tarrant County.

4 Model of Spatial Agglomeration

To what extent do firms benefit from spatial agglomeration in the private market for leasing mineral rights when there are complementarities from owning the rights to contiguous clusters of land and more stringent contracting is costly? Further, how do the equilibrium market structure and total welfare change when firms are restricted to sign more stringent and costly leases? Studying these questions requires estimating a structural model of lease negotiation that captures the trade-off in firms' preferences between the value of spatial agglomeration and the costs of signing leases with more landowner concessions. Spatial agglomeration is valuable to firms amassing the rights to large, contiguous acreage rendering them eligible to apply for a drilling permit. Landowner concessions increase firms' contracting costs by requiring that firms comply with additional environmental testing and restrictions to noise, traffic, and well locations, among other limitations to firm behavior. However, landowner concessions protect landowners from future drilling disamenities. Understanding how higher contracting costs affect the market for leases (i.e. entry, exit, and spatial agglomeration) is important to approximate the resulting changes in firm, landowner, and total welfare.

The following subsections describe a model of lease negotiation that captures poignant industry features including firms' preferences for spatial agglomeration and multi-dimensional contracts, bilateral decision-making by firms and landowners, preference heterogeneity across firms and landowners, and endogenous and unobserved choice sets, whereby the ability to sign a lease with a specific landowner hinges on all firms' and landowners' modeled preferences. Estimating a model incorporating all of these features is complicated and requires several simplifying assumptions that are also described in the text. To my knowledge, this is the first paper to structurally model the private lease negotiation market, and it is among the few empirical, one-to-many match papers assuming non-transferrable utility (NTU). Finally, the model contributes to the empirical, one-to-many, NTU match by adding a match externality that induces complex preferences through the aggregate measure of spatial agglomeration.

4.1 Spatial Complementarity

In the two-sided lease market, I observe firms signing many leases with landowners owning mineral rights across Tarrant County, and for each negotiation, I observe the final contract outcome and location along with parcel and firm characteristics.[36] I model the final lease negotiations as a one-to-many match in which a single firm signs leases with many landowners. Each negotiation is the result of bilateral decision-making based on firms' and landowners' ranked preferences. In contrast to the traditional discrete choice literature, matching models grant autonomy to both sides of the market whereby firms extend lease offers to landowners and landowners have the option to reject undesirable offers. Further, the firm and landowner choice sets are unobservable in the lease market, and the matching framework flexibly endogenizes the choice set using the preference rankings of all market participants by approximating the market assignment using the Deferred Acceptance Algorithm, which is described in Section 5.

The underlying preferences are represented by distinct firm and landowner value functions through assuming non-transferrable utility (NTU), and they are comprised of observable and unobservable characteristics and modeled according to the Berry and Pakes (2007) pure characteristics model. Because firms and landowners likely value different aspects of the leasing agreement, I use exclusion restrictions to separately identify firm preferences from that of the landowners. The distinct value functions are jointly optimized in the NTU setting, and transfers exchanged between firms and landowners are assumed to be established before the firms and landowners agree to sign leases.[37] In particular, Equations in (3) capture the firm j's and landowner i's values for potential leasing partners through v_{ij} and u_{ij}, respectively. Firms value leases signed with each landowner based on parcel (X_i) characteristics and the pecuniary and non-pecuniary contract terms (θ_{ij}) that are characterized by $f(X_i, Z_j, \theta_{ij}; \beta)$. Similarly, landowners' values for observable, negotiation-level characteristics are characterized by $g(X_i, Z_j, \theta_{ij}; \alpha)$.

$$\begin{aligned} v_{ij} &= \Lambda_{firm} + f(X_i, Z_j, \theta_{ij}; \beta) + \beta share_j^m + \eta_{ij} \\ u_{ij} &= \Lambda_{parcel} + g(X_i, Z_j, \theta_{ij}; \alpha) + \xi_{ij} \end{aligned} \tag{3}$$

[36] Ideally, one would be able to observe whether a landowner receives multiple offers from the observed and/or competitor firms along with the evolution of those contracts through repeat interactions if there are repeat interactions.

[37] Assuming transferrable utility implies that firm and landowner values are additive and that transfers are co-determined with the match assignment by optimizing the joint surplus. Section 4.6.1 describes the NTU modeling choice and threats to that assumption in greater detail.

Each observed lease is signed having agreed to an unobserved bonus payment, or fixed transfer to the landowner at the date the lease is signed, so unobservables are an additional determinant of firm and landowner preferences.[38] Each firm and landowner value includes an unobservable and additively separable, negotiation-level shock, η_{ij} and ξ_{ij}, respectively. These measures are assumed to be uncorrelated with observables, unobserved to the econometrician, and observed by firms and landowners. The unobservables represent attributes of the lease or negotiation process known to firms and landowners signing the lease and rendering a particular negotiation more or less attractive to the two parties. In addition to bonus payments, unobservable attributes might account for a particularly effective sales pitch, strong negotiation skills, or a parcel unencumbered by trees, among other examples. Further, inclusion ensures that firms' and landowners' preference rankings are strict and the modeled equilibrium is unique.[39]

In addition to unobserved bonuses and landowner concessions, landowners are owed royalty payments for any oil or natural gas extracted and sold from their mineral estate, which is the final, modeled contract dimension. I combine observed royalty rates (r_{ij}) with monthly well production[40] (q_{wt}) and gas price (p_t^{ng}) data to calculate the expected royalty payments from a future well as defined in Equivalencies (4), which is added to firm and landowner values. The annualized expected royalty payments are then used to normalize and scale the value functions representing the two sides of the market, and the normalization allows estimates for the non-pecuniary attributes of firms' and landowners' preferences to take on a monetary interpretation. Annualized expected royalty revenues are summarized for firms and landowners in Table 2b.

$$\begin{aligned}
&\text{Grantee revenue: } \Lambda_{firm} \equiv 0.05(1-r_{ij})\frac{a_i}{\sum_{\forall i' \in w} a_{i'}} \sum_{t=1}^{T} q_{wt} p_t^{ng} \\
&\text{Grantor revenue: } \Lambda_{parcel} \equiv 0.05 r_{ij}\frac{a_i}{\sum_{\forall i' \in w} a_{i'}} \sum_{t=1}^{T} (q_{wt} p_t^{ng})
\end{aligned} \tag{4}$$

The final element of firms' values measures the effect of spatial agglomeration on firms' preferences for all potential landowner matches. Firms must own the mineral rights to all

[38]As noted in Section 2.3, bonus data is reported for only 2% of the sample. I report raw correlations that suggest a "good" lease with higher royalty rates and more landowner concessions also has higher bonus payments using the small sample. This observation allays concern that landowners are being compensated for accepting leases with fewer landowner concessions.

[39]Section 5 describes the equilibrium selection mechanism used to identify the described one-to-many matching model.

[40]Natural gas production has a steep decline rate in that a bulk of the natural gas is produced within the first one or two years of production. Therefore, using observed gas production for wells drilled at least one year before the end of the data is a reasonable approximation.

subsurface acreage from which they want to extract before submitting a drilling permit application to the TRC. This regulatory incentive suggests that firms directly value their ability to lease a large number of spatially proximate parcels, especially in Tarrant County where parcels are not large enough to support a single well.[41] Spatial agglomeration is measured as the share of lease signed by firm j in geographic market m, or $share_j^m$. Allowing firms' value to vary with market structure complicates firms' preferences because they are no longer negotiation-specific, but rather, preferences depend on the total lease market assignment.

Firms and landowners use their value functions to rank their respective preferences across all potential leasing partners. The following subsections describe the model's equilibrium and assumptions that are necessary to estimate a one-to-many, NTU matching model with complex preferences, whereby firms' preference may induce complementarity, and equilibrium may be nonexistent, multiplicitous, or unstable.

4.2 Myopic Estimation Function

Firms' negotiation values, which include the direct effect of firms' market shares, vary with the attributes of specific lease partners and the entire market assignment of leases signed by all firms. Any deviating firm and landowner pair must consider not only how their payoffs differ under re-assignment, but also how the payoffs of all other market participants respond to their deviation, which potentially shifts firms' preferences through changes to $share_j^m$. When a firm j leases more in a market m, firm j's negotiation values for all parcels in that market increase. Firm j leasing more in market m decreases the number of leases signed by other firms $j' \neq j$, thereby decreasing j''s negotiation values for all parcels in m. Further, firm j leasing more in market m implies that j leases fewer parcels in market $m' \neq m$.

Sasaki and Toda (1996) and Hafalir (2008) propose using an estimation function approach to deal with the complexity of preferences defined over the market assignment. I follow an even more restrictive approach taken by Uetake and Watanabe (2013) and Baccara, İmrohoroğlu, Wilson, and Yariv (2012) that assumes firms have boundedly rational beliefs about other firms' actions through use of a myopic estimation function.[42] A myopic estimation function maps the set of lease partner choices to the estimated market shares observed for each firm across all geographic markets, or $\mathcal{F}_j : \cup_{i \in \mathcal{N}} \mu_j(i) \to \mathbb{R}_+$, where $\mu_j(i)$

[41] The relationship between market structure and "time to drill" in the data is addressed directly in Section 7.1 and Table 9, which reports a reduction in the time to begin drilling (and presumably profiting from oil and natural gas sales) for firms with greater market share.

[42] The empirical myopic estimation function approach follows from the theory proposed by Sasaki and Toda (1996) and Hafalir (2008). Other theoretical matching with externalities literature include Bando (2012) and Pycia and Yenmez (2015).

describes a match between firm j and landowner i.[43]

In practice, myopic estimation fixes firm behavior and assumes that each agent believes all other agents will sign the total number of leases they are observed signing in the data, which is denoted as $\bar{q}_j$.

4.3 Pairwise Stable Equilibrium

Based on the value functions described in Equations (3) and firms' beliefs, firm j extends offers to landowners in sequence until they amass $\bar{q}_j$ leases, or there are no remaining, profitable offers to extend. Reciprocally, landowners hold on to their most preferred and acceptable match and reject all others until they receive no more offers. Offered and accepted leases across the two sides of the market are modeled as a series of matches mapping from the sets of firms to landowners, where a match between firm $j \in \mathcal{J}$ and landowner $i \in \mathcal{N}$ is denoted $\mu_j(i) : \mathcal{N} \to \mathcal{J} \cup \{0\}$.[44] A particular match between j and i is predicated on the contract value denoted θ_{ij}, which includes landowner concessions and royalty rates. The set of contract values and matches between the two sides of the leasing market are assumed achieve a pairwise stable equilibrium.

Pairwise Stability: Stability is defined in terms of firm j's value, v_{ij}, and landowner i's value, u_{ij}, the estimated measure of firm market concentration, $share_j^{m*}$, and the support of contract values available to firm j, $\mathcal{D}_j = \cup_{i \in \mathcal{N}} \{\theta_{ij}\} \cup \{0\}$.

1. *Individual rationality*:
   (a) Landowners: $u_{ij} \geq 0$.
   (b) Firms: $\nexists\, \tilde{\theta}_j \subset \mathcal{D}_j$ s.t. $V_j(\tilde{\theta}_j, share_j^{m*}) \geq V_j(\theta_j^*, share_j^{m*})$, $\sum_{i \in \mu_j(i)} \mu_j(i) \leq q_j$.
2. *No blocking*: $\nexists\, j' \subset \mathcal{J}$ and $\nexists\, i' \subset \mathcal{N}$ such that
   (a) Landowners: $u_{i'j'} \geq u_{i'j}$
   (b) Firms: $V_{j'}(\theta_j^* \backslash \{i\} \cup \{i'\}, share_j^{m*}) \geq V_{j'}(\theta_j^*, share_j^{m*})$

The first *individual rationality* condition requires firms and landowners have positive negotiation values for each potential match in their acceptable sets. Firms have the added restriction that there not be another available set of contracts preferred to the matched set θ_j^* given the estimated market structure $share_j^{m*}$. The second *no blocking* condition states that

[43] To simplify notation, I exclude the empty set from the union of potential matches available to firm j, though, as will become evident in the next section, firms can feasibly not match (and sign leases) with any landowner.

[44] $\{0\}$ denotes not signing a lease.

there does not exist a firm, j', and landowner, i', pair preferring to match with each other over their observed matches. Since the model includes a match externality (i.e. $share_j^m$), the stability condition must hold for the estimated market assignment, $share_j^{m*}$. Threats to assuming pairwise stability are addressed in Section 4.6.2.

In general, a pairwise stable equilibrium is not guaranteed to exist when preferences are complex and exhibit complementarity through the match externality, and if it exists, it is not guaranteed to be unique. In particular, including a firm's $share_j^m$ allows the preference for a single match to depend on the firm's matches to other, nearby parcels. Ignoring the unobserved, match-level attribute, a situation where $f(X_i, Z_j, \theta_{ij}; \beta) \leq 0$ and $\beta share_j^m > -f(X_i, Z_j, \theta_{ij}; \beta)$ results in $v_{ij} \geq 0$ and a potential instability among firms competing to sign these marginal leases.[45] Intuitively, there may be parcels of land with low acreage or that are located on the periphery, and when evaluated independently, acquiring the mineral rights is not valuable to the firm. However, if that firm has negotiated a large concentration of nearby leases, the values of the low attribute parcels increase.

Practically, the equilibrium is verified post-estimation, and the equilibrium is more likely to exist in the lease market because the match externality is an aggregate measure of the market assignment, which is a weaker form of complementarity. Instability, and nonexistence, is a greater threat when specific match partners are important; however, the lease model is only valuing the firm-specific market shares and not the specific firm-landowner pairings, which is more similar to matching with couples theoretical literature cited in Section 4.2. This model may be useful approximating assignments in other two-sided markets in which complex preferences can be distilled into aggregate measures like firms hiring a diverse workforce comprised of fractions of worker types.

4.4 Heterogeneous Preferences

Finally, the specified value functions underly heterogeneous firm and landowner preferences, which may induce multiple equilibria. In particular, the model permits estimating firm- and landowner-specific preferences for particular parcel and firm characteristics. Among firms signing leases, some are operators that drill wells and others are landmen who specialize in land leasing. These two firm types feasibly place different values on parcel attributes, and the model is estimated in a way that allows for firm and landowner preferences to vary across firm types.[46]

[45] The appendix includes a description of a simple model with complements that adapts a model described in Che, Kim, and Kojima (2014) to the lease market setting.

[46] The model could potentially estimate more complex preference heterogeneity; however, doing so would increase the computational complexity due to the large market.

Second, neither side of the market exhibits a vertical preference rankings, which is to say that firms' rankings of all landowners are not unified and visa versa for landowners ranking firms. Landowners from wealthy neighborhoods may value signing leases with landmen over operators, for example, hoping to extract bonuses with a lower probability of drilling. In addition to observable, heterogeneous preferences, the model includes unobserved, match-specific shocks for all potential firm and landowner pairs, which further induces non-vertical preference rankings for both firms and landowners.

To mitigate potential multiplicity, I estimate the model with an equilibrium selection mechanism that assumes firms always extend offers to landowners, which mimics observed industry behavior, and solves the matching assignment with the *firm-optimal* equilibrium.

4.5 Market Power & Spatial Agglomeration

The market power model presented in Section 3 fits into the matching framework through Equation (5). While quality is not endogenously determined in the model of spatial agglomeration, the correlation in the data between the endogenously determined market structure and the firms' lease quality is negative and used to identify parameters describing firms' preferences.

$$\begin{aligned} v_{ij} &= \Lambda_{firm} + f(X_i, Z_j; \beta) + \beta share_j^m - \beta^{qual}\theta_{ij}(share_j) + \eta_{ij} \\ u_{ij} &= \Lambda_{parcel} + g(X_i, Z_j; \alpha) + \alpha^{qual}\theta_{ij}(share_j) + \xi_{ij} \end{aligned} \tag{5}$$

A rough test of whether the leasing market with spatial concentration most benefits firms or landowners is captured by relative effects of market share across firm and landowner values as in Equation (6).[47]

$$\begin{aligned} &\text{Firm Value:} \qquad \frac{\partial v}{\partial share} + \frac{\partial v}{\partial \theta}\frac{\partial \theta}{\partial share} \\ &\text{Landowner Value:} \qquad \frac{\partial u}{\partial \theta}\frac{\partial \theta}{\partial share} \end{aligned} \tag{6}$$

Estimates from the matching and lease quality models approximate the firm and landowner values to market concentration. The model of lease negotiation described throughout Section 4 identifies the marginal value of increased market share, which is captured by $\frac{\partial v}{\partial share}$, and the marginal cost (value) of landowner concessions captured by $\frac{\partial v}{\partial \theta}$ and $\frac{\partial u}{\partial \theta}$. The lease quality models described in Section 3 identify the effects of market structure on lease quality through

[47] These two sides of the market are not directly comparable because they are normalized by different measures of expected profit for any given firm and landowner pair. Further, the coefficient capturing $\frac{\partial \theta}{\partial share}$ is not estimated with a money metric as are coefficients in the matching model.

$\frac{\partial \theta}{\partial share}$ for different types of landowner concessions.

4.6 Model & Estimation Assumptions

The model set-up and estimation rely on several assumptions or simplifications describing the types of information firms and landowners have when they sign leases, transfers observed in the market, equilibrium imposed on the leasing market, and potential for strategic behavior between firms. I detail more specifically the threats to approximating the lease negotiations using non-transferrable utility and imposing that the observed matches satisfy pairwise stability.

4.6.1 Non-Transferrable Utility

The lease market assignment is approximated assuming non-transferable utility to capture the distributional costs and benefits of leasing across firms and landowners and to account for the multidimensionality of lease contracts. Non-transferrable utility (NTU) is somewhat of a misnomer in the sense that it does not eliminate the existence of transfers, but imposes that transfers are agreed upon before assignment, or in the lease market, before firms extend lease offers to landowners. Transferable utility (TU) imposes that firms' and landowners' values are additively separable (with a constant exchange rate connecting the values of the two sides of the market), jointly maximizes the total surplus, and co-determines market assignment with the transfers. I argue that firms and landowners have different, expressed interests in signing leases, and my ability to estimate separate preferences hinges on assuming their value functions are exogenously given, as described in Section 4. Second, the TU setting does not readily handle multidimensional contracts like oil and natural gas leases. However, the proposed lease negotiation model assuming NTU accounts for three, primary dimensions, including royalties, landowner concessions, and unobserved bonus payments. Non-transferrable utility is violated if leases are simultaneously and heavily negotiated as a part of the match, and to some extent, there is probably "back and forth." However, the data is limited to final firm and landowner matches along with the contents of their final, negotiated lease, and I am able to make progress studying a complex set of private negotiations and the resulting contract terms under the proposed assumptions of the one-to-many, NTU model.

4.6.2 Pairwise Stability

Equilibrium in the leasing market is defined by pairwise stability that imposes there not be any post-leasing transfers. This is a strong assumption for the leasing market because there are likely unobserved lease transfers prior to permitting a well. However, when the leasing firm is not an operator of the well, it is difficult to identify in the data whether there was a lease transfer or non-operators maintained a royalty interest stake in the drilled well. Further, I am not aware of data that describes these transfers explicitly.

By estimating the model using pairwise stability, the model separates the leasing decisions from the permitting decisions and assumes that pre-permitting transfers occur at fair market value and all participating firms have perfect information. While these assumptions are strong, they are not unreasonable among knowledgeable oil and natural gas industry participants. In particular, firms have access to the same futures price data and monthly production values. Relatedly, more than one firm may be leasing on behalf of a large operator like Chesapeake. Collusion across firms may induce bias that is described in greater detail in the appendix; however, to estimate the model, it is assumed that firms leasing on behalf of an operator know the fair market value for their leasing efforts regardless of whether it is realized as fixed payments or royalty interest stakes.

4.6.3 Other Assumptions

Given firms' and landowners' values, the model assumes that firms rank all properties across Tarrant County and, reciprocally, that landowners rank all potential firm offers, which implies that firms and landowners act with full information that enables complete rankings. Each value function includes annualized, expected royalty payments split between firms and landowners, which is a significant information burden especially for landowners that are unfamiliar with the oil and natural gas industry. However, because expected future profit is used to monetize the preferences for non-pecuniary attributes, miss-specification of the profit can be added to the error term in the landowner values.[48]

The matching model is estimated as a static, one-shot equilibrium, so it does not account for any dynamics in matching across periods in the data, and estimating a dynamic matching model requires an additional level of computational complexity beyond the present analysis and existing empirical literature. However, two important features of the data suggest that a static framework likely captures the desired market interactions of interest. The future expected royalty payments from drilled wells remain steady across time even though the royalty rates have a slight upward trend pre-2009. Additionally, assortativity regression

[48]In particular, the landowner values used to estimate the model is $u_{ij} = \Lambda(X_i, Z_j) + g'(X_i, Z_j, \theta_{ij}; \frac{\alpha}{\alpha_0}) + \xi_{ij}$ where $\Lambda(X_i, Z_j)$ is the money metric with a coefficient α_0 used to normalize the values of the non-pecuniary attributes estimated in $g'(X_i, Z_j, \theta_{ij}; \frac{\alpha}{\alpha_0})$. Miss-specification results from landowners over or under valuing future profit from a lease by λ, where $u_{ij} = \Lambda_0(X_i, Z_j) + \lambda_{ij} + g'(X_i, Z_j, \theta_{ij}; \frac{\alpha}{\alpha_0}) + \xi_{ij}$, which, if independent of the actual expected production, can accounted for with the match level unobservable. Another option may be to mitigate measurement error by instrumenting the landowner value function using a control function approach.

results described in Section 7 and reported in Table 8 are impervious to time fixed effects as are the market power estimates described in Section 6.[49] These observations suggest that statistical moments based on the static matching outcomes identify important patterns leading to the final market structure that is observed in the data.

5 Identification & Estimation

This section describes the estimation strategy used to identify the two-sided model of one-to-many, non-transferable utility (NTU) matching with a match externality, which includes a description of the specific statistical moments and exclusion restrictions that identify the model, estimation sequence, and Deferred Acceptance Algorithm that simulates the two-sided match.

5.1 Identification

Point-identification of the model stems from the set of statistical moments, exclusion restrictions, and the use of an equilibrium selection mechanism. One-to-many, NTU matching models are prone to have multiple, stable equilibrium unless researchers impose an equilibrium selection mechanism or restrict preferences.[50] The equilibrium selection mechanism used to estimate the leasing model assumes that firms extend offers to landowners, which mimics industry standards and results in a *firm-optimal* equilibrium. I describe the exclusion restrictions and statistical moments in the following subsections.

5.1.1 Exclusion Restrictions

Firm and landowner negotiation values are distinct and there are features of the negotiation that shift firms' preferences without shifting landowners' that are useful exclusion restrictions helping identify the model. Firms value parcel features that affect costs including the size of parcels and proximities to infrastructure, like pipelines and a future well

[49] The Appendix reports lease quality regressions using firms' geographic market structure and average lease quality (within a market), and there is still evidence that firms exert market power when measured at the geographic market level.

[50] Boyd, Lankford, Loeb, and Wyckoff (2013) selects an equilibrium that results from assuming employers extend offers to employees (teachers). Agarwal (2015) restricts hospitals preferences for residents to be vertical, which ensures the pairwise stable match is unique and reduces computational complexity. Uetake and Watanabe (2013) set estimates their model, which admits multiple equilibria; however, their ability to estimate parameter bounds depends on firms having substitutable preferences that guarantees existence and allows them to apply the lattice structure and use theoretical results by Hatfield and Milgrom (2005) to inform their estimation strategy.

site.[51] These cost factors have a direct impact on firms' values by decreasing the number of negotiations required to achieve a large enough leased mineral acreage and decreasing expenditures on gathering lines that connect the drilled well to a major pipeline. Further, these measures are all parcel-specific. Landowners value a lease based on firm characteristics and early exposure to drilling. In particular, pre-2004 drilling behavior is not necessarily predictive of the final spatial drilling pattern that permeated the county from 2004 through 2013 because of large, technological changes in the industry. The exclusion restriction supposes that a landowner living near pre-2004 well development may be more receptive to signing a lease that allows them to profit, which is independent of firms' final, spatial leasing preferences.[52] Finally, firms' values include $share_j^m$, which is valuable because a higher share reduces the time to permitting and shifts their preferences independent of landowners' preferences. Other, less coarse measures of neighborhood leasing patterns may be valuable to landowners and is an area of future research.[53]

5.1.2 Statistical Moments

Statistical moments describing the joint distribution of match firm and parcel characteristics, within group variation, and market structure variation help identify the estimates parameterizing firm and landowner preferences. Table 3 lists each statistical moment beginning with the first set that describes the joint distribution and covariance across matched firm and landowner characteristics, or general assortativity, whereby assortativity in the data is described in Section 7.

Second, I use information from the "many" landowners signing leases with a single firms as first proposed by Agarwal and Diamond (2014) (and applied to the resident-to-hospital match in Agarwal (2015)) for instances when there is not perfect assortativity in the market, which is described in Table 3 under *Firm-level Moments*. Firms offering more landowner concessions are not necessarily signing leases for larger parcels that are located nearer to the future drill site, which are both attractive features, and there may be an unobservable component leading to behavior that is not perfectly assortative. Moments describing firms' aggregate behavior in a one-to-many match allows one to identify the parameters in the

[51] Due to regulated well density and spacing restrictions that are coupled with established neighborhood and subdivision restrictions, assuming wellpad location is exogenous is more reasonable.

[52] As noted in Section 4.6, the matching model is estimated as a one-shot, static equilibrium, and the pre-2004 drilling pattern is not predictive of the final spatial lease pattern even though a dynamic setting might reveal that early leasing in Tarrant occurred nearer to the the northwest corner, a relationship used to estimate the market power models described in Section 3.

[53] Landowners may prefer signing a lease if their neighbors have already signed knowing that the well is going to be drilled regardless. This form of preference is more complex than the current setting because preferences may depend on landowners' neighbors specific match partners (firms) and lease contents.

presence of unobservables and imperfect assortativity. This is particularly relevant in an atypical drilling setting like Tarrant County where one might not be able to fully capture the observable attributes driving firms' sorting behavior across the geographic markets and small land parcels within markets.

Market-level and Market Structure Moments identify the firms' preferences for signing leases across geographic subregions of Tarrant County and are new moments to the existing matching literature that help identify the effect of the match externality, or $share_j^m$, in firms' value functions. *Market-level Moments* utilize the geographic clustering of landowners' parcels by calculating within-market moments that identify parameters describing how firms sort across space. *Market Structure Moments* penalize simulated market structures (output from the Deferred Acceptance Algorithm described in Section 5.2) not matching the observed market structure in the data. Table 4 describes the observed market structure across Tarrant County, and it captures some of the variation in the data that is used to identify the effect of the endogenous $share_j^m$ in firms' values. On average, there are about 442 leases per geographic market, and there are 394 markets in the data. The average market share across firms and markets in the data is 0.13 (0.22).

5.2 Estimation

The model is estimated using a minimum distance estimator (McFadden (1989); Pakes and Pollard (1989); Gourieroux and Monfort (1997)) where the estimated parameter set $\hat{\Omega}$ minimizes the simulated objective function (7). The moments of the observed data are denoted $\hat{m}$ while the average moments from the set of simulated outcomes are denoted $\hat{m}(\Omega)$.[54]

$$||\hat{m} - \hat{m}^S(\Omega)||_W^2 = (\hat{m} - \hat{m}^S(\Omega))' W(\hat{m} - \hat{m}(\Omega)) \tag{7}$$

Estimating the model requires simulating the matches between firms and landowners for each draw of the unobserved, match-level heterogeneity, η_{ij}^s and ξ_{ij}^s.[55] The deferred acceptance algorithm[56] facilitates a pairwise stable matching for each draw.[57] Given the simulated draws, the estimation sequence proceeds:

1. **Calculate negotiation values:** For each draw of the error terms (η_{ij}^s and ξ_{ij}^s) and

[54]The parameter estimates reported use an identity weight matrix which results in consistent estimates; however, efficiency is increased with a weight matrix noted in the estimation appendix.

[55]The m superscript is exchanged for a s superscript to simplify notation since i is unique in the data across markets and s indicates the simulation draw for each term.

[56]Gale and Shapley (1962) first demonstrated that the deferred acceptance algorithm yields a stable equilibrium under representative and substitutable preferences.

[57]The simulated draws are taken from a Halton sequence to reduce the computational magnitude of the problem. Train (2000) Train (2009) describes the use of Halton draws.

assuming that $share^m_{0,j} = share^m_j$ that is observed in the data, calculate firm and landowner negotiation values.

2. **Rank firm and landowner preferences:** Determine the accepted sets of match partners for each firm and landowner, then rank the accepted sets based on the negotiation values.
3. **Deferred acceptance match ($\mathcal{J}$-optimal):**
   (a) Firms extend offers to their most preferred landowners.
   (b) Landowners accept their most preferred offer.
   (c) Firms continue extending offers in rank order of their preferences for landowners.
   (d) Landowners hold their most preferred offers and reject all others.
   (e) Continue offering and accepting until pairwise stability is reached.
4. **Calculate the new share, $\widehat{share_j}^m$:** The outcome of the deferred acceptance algorithm is the set of matches between firms and landowners across geographic markets that can be used to calculate an estimated share, $\widehat{share_j}^m$.
5. **Calculate moments:** Use the estimated $\widehat{share_j}^m$ and participant characteristics resulting from the simulated match to calculate the simulated moments.

This sequence follows for each guess of the parameter space, $\hat{\Omega}$, and each draw of the error terms, η^s_{ij} and ξ^s_{ij}, and is proceeded by calculating the resulting joint distributions of the matched pairs' characteristics, along with the group-level moments and simulated market structure described in Table 3. The simulated draws are constant across each guess of the parameter set. After estimating the model, I verify whether the parameters describe an equilibrium by ensuring the market shares for firms across Tarrant County are stable. The model parameters are estimated using a random sample of matches between roughly 30 firms and 60,000 landowners across 105 markets, and the model fit is tested on the entire dataset consisting of 250,210 matches across 394 markets. The appendix includes added details about inference for the estimated parameter set and other computational details, including a Monte Carlo testing the efficacy of the market structure moments.

6 Results: IV Model of Market Power

I begin by estimating causal relationships between firm market structure and landowner concessions capturing whether firms exercise market power in private contracting. Lease quality is multi-dimensional and comprised of royalty rates, primary term lengths, bonus payments,[58] and specific clauses designed to restrict firm behavior in varying ways. I estimate the effect of market structure on lease quality where market structure is measured as the share of leases signed by a single firm in a geographic region of Tarrant County. The models estimating the effect on royalty, term length, and whether the lease includes a *Post-production Costs* clause include market characteristics like oil and gas 18-month futures prices and measure of volatility. Prices are added to those specifications because those contracting terms have pecuniary implications. Royalties dictate how future well profits are split between firms and landowners, term length determines the latest date at which a well can be drilled and begin generating profit, and *Post-production Costs* limits which costs landowners are responsible for paying before they are owed royalties.[59]

Tables 5 and 7 report the ordinary and two-stage least squares estimates of the effects of market structure on each measure of lease quality. The competition measures, or market structure, are the firms' cumulative shares in a particular geographic market at the dates in which leases are signed. In addition to competition, the models are estimated with year-level fixed effects and controls that describe the parcel characteristics like the size of the parcel and proximity to the well lateral, which are physical characteristics that might matter to a firm amassing mineral rights from which they want to extract. Finally, each model reports standard errors that are clustered by geographic market to address potential correlation across leases signed by households located near one another.[60] Equations (8) describe the first and second stage estimating equations in which θ_{ij} takes on values for the different measures of landowner concessions and $share_j^m$ is firm j's cumulative market share in market m in which landowner i is located.

$$\begin{aligned} \text{First Stage:} \quad share_j^m &= \alpha_0 + \alpha_1 X_i + \alpha_2 Z_j + \chi_{ij} \\ \text{Second Stage:} \quad \theta_{ij} &= \delta_0 + \delta_1 X_i + \gamma \widehat{share_j^m} + \epsilon_{ij} \end{aligned} \tag{8}$$

Tables 5 and report the OLS and 2SLS results for lease quality measures that have pecuniary value, which includes *Royalty Rates*, *Term Length*, and *Post Production Costs*. The

[58]Bonus payment regressions are omitted from the main text due to the small sample size (roughly 5,000 observations); however, the negative relationship between bonuses and greater market concentration is similar to that observed for the other measures of lease quality and are reported in the Appendix.

[59]Legal cases in Pennsylvania overlaying the Marcellus shale and involving leasing/drilling companies regard lower royalties paid due to post production cost deductions. The court sided with industry citing that "royalty was not defined in state law." Including a clause that explicitly states what are post production costs or puts a cap on the amount of deductible costs clarifies the expected royalty payments for both firms and landowners. `https://stateimpact.npr.org/pennsylvania/tag/royalties/`

[60]Wellpad is the preferred geographic market, which describes clusters of wells drilled nearby with horizontal laterals extending in different directions. However, the data describing leasing and permits is not easily merged based on a unique identification number. Rather, the leases are approximately assigned to wells and wellpads based on the proximity of leases (parcels) to the nearest well lateral.

estimates for the primary variable of interest, *Lease Share*, are reported in the first row. Comparing estimated effect of *Lease Share* in the OLS and 2SLS models, the instrument increases the magnitudes of the significant effects on *Royalty*, *Term Length* and *Post Production Cost*. Focusing on the 2SLS estimates, I find that a greater market share has a negative effect on *Royalty* (-0.017*) and the inclusion of a *Post Production Cost* clause (-0.771**) and a positive effect on *Term Length* (35.978***). Overall, these results suggest that firms exert market power in the pecuniary terms offered to landowners, thereby paying them lower royalties, holding the mineral rights longer, and excluding restrictions to cost deductions taken out of owed royalties. A firm with a fifty percent market share is about thirty-five percent less likely to sign a lease with a *Post Production Cost* clause (-0.771*0.5).[61] Royalties are paid to landowners based on the size of their parcel relative to the size of the leased drilling unit, and the second column of Tables 5 and report model estimates when $Royalty*\frac{land}{total}$ is the dependent variables. The estimated models suggest that a firm's increased market share reduces the royalty per square foot leased owed to landowners. *Oil Volatility* leads to more landowner concessions, which is attributable to greater confidence in future, stable natural gas prices. Greater *18-Mon. NG Future* prices lead to lower absolute royalties and greater royalty per square foot leased, shorter term lengths, and more post production cost restrictions, which describes a situation where the firm has a greater expectation over the future profitability of the well.

The last rows of the upper panel of Table 6 reports the P-statistics for Hansen's Overidentification test and the T-statistic for the Wu-Hausman Endogeneity test. The statistics suggest that we cannot reject the null hypothesis that the overidentifying restrictions are valid and that there is endogeneity between market structure and lease quality outcomes. The lower panel reports partial first stage estimates (excluding the estimated effects of the other exogenous variables and year fixed effects), and I find that *Pre-2004 nearby producing wells* has a positive relationship with cumulative *Lease Share* and *Pooling Approved* has a negative relationship, which is intuitive based on the identification discussion in Section in 3.

Table 7 reports the results for non-pecuniary lease quality measures, or auxiliary clauses that have been grouped by clause types as described by Table 1b. The primary estimates of interest are reported in the first row of the second panel, and I find consistent evidence of market power that leads to fewer landowner concessions. The first, *Full Set* is a count measure of all landowner concessions in the analysis, and I find that firms with fifty percent market share offer roughly thirty percent fewer clauses. Among the *Dis-amenity* clauses, a fifty percent market share leads to around thirty (-0.66*0.5) percent fewer clauses, which is

[61] Market power results are not sensitive to excluding controls.

roughly 1.5 fewer dis-amenity clauses out of five total. In the Appendix, I demonstrate that firms exercise market power in lease terms when performing the analysis using individual clauses, as opposed to the landowner concession type measures (ex. *Dis-amenity*, *Surface*, *Legal* bundles, etc...). Comparing OLS in the upper panel to 2SLS in the lower panel, the effects of market power are amplified with use of the instruments, with an exception that the effect on *Surface* is no longer significant.

Specifications reported in the Appendix demonstrate robustness to a different definition of geographic market, selections of instrumental variables,[62] definitions of market structure,[63] and restrictions to the data that include only those leases signed before 2009, which isolates the analyses to the height of leasing activity in Tarrant County and before the precipitous decline in natural gas prices. The negative relationships between market structure and landowner concessions are robust to these variations in addition to exclusion of other control variable. Further, the Appendix includes fixed effects regressions that estimate the effects of market share on lease outcomes that control for unobservable heterogeneity in firm identity, year and month, and geographic market, and the results are consistent with the hypothesis that firms exert market power in contracting outcomes.

7 Results: Matching Model of Spatial Agglomeration

7.1 Assortativity

Before presenting the results of the matching model, I present reduced form evidence motivating the modeling choices including assortativity across the two sides of the market and the value of spatial concentration for future drilling behavior. Table 8 describes assortativity between firm and landowner characteristics. Each column in each panel reports a separate OLS regression of an attribute on the set of attributes characterizing the other side of the market capturing firms' assortativity in Table 8a and landowners' assortativity in Table 8b. Broadly, the observable characteristics used to model the leasing market have largely significant relationships. The most valuable parcel in term of expected profit are those with the largest land size (1.580***) and located nearest to infrastructure (0.628*** associated with proximity to the pipeline), not with a higher property value (-0.359***), as suggested by the first column of Table 8a. The second column reports the relationships between firm characteristics and the lease quality, and it suggests a negative relationship between market structure and quality (-0.579***), paralleling the discussion in Section 3 de-

[62] Additional instruments include pre-2004, nearby producing wells in Tarrant and across Texas.

[63] Other measures of competition include the Herfindahl-Hirschman Index, aggregate firm share, and the firm count by market are used to estimate similar models.

scribing the lease quality model. Additionally, lease quality and expected profitability have a strong positive relationship (2.094***). In Table 8b, lease quality is negatively related to profitability (-0.013***), and intuitively, parcels located nearer to the well are correlated with higher expected profit (0.913*** and 0.795***), as reported in the first column. In the last column and similar to the estimates in Table 8a, lease quality is negatively related to market structure (-0.137***).

Table 9 reports results that describe relationships between market structure and the timing of firms' permitting, production, and leasing decisions. In particular, the first two dependent variables (columns) describe the time, in months, from the leasing decision until the well is permitted and begins production. Table 9 suggests a larger market share reduces the time until firms move to more profitable stages of well development. The effects of firms' market share is larger for the relationship with time to production (the second columns). The third column of Table 9 estimates a relationship with the count, in days, between the last lease signed and the current leasing decision. As measured in the other specification, the effect of market concentration is negative and significant (-19.709***), indicating that a larger market structure decreases the incremental time between signing leases and moving more quickly through the sequence of leasing decisions.

7.2 Estimates

The structural estimates from the one-to-many matching model are reported in Table 10 split between the parameters characterizing firm values as reported in Table 10a and those characterizing landowner values in Table 10b. The model captures heterogeneity in firm preferences for parcel attributes as defined by the second column of Table 10a. Each estimate has a monetary interpretation because they are normalized by the expected, annualized royalty payments where the mean, annualized payment for a parcel in the data is 140.04 (140.04 x 3 for firms, roughly) as reported in Table 2b. In general, the estimates of the matching model fit the hypotheses proposed in Section 4. Firms view more landowner concessions as costly while landowners value the added protection, and firms value spatial agglomeration.

Beginning with firm preferences, the estimates suggest that firms view more landowner concessions as costly as indicated by the estimates for *Lease Quality* (-5.825***) in Table 10a. Using the *Dis-amenity Bundle* summary statistics in Table 1b, an increase in clauses of 0.238, which is equivalent to one additional clause in the *Dis-amenity Bundle*, results in a decreased firm value of -5.825. Increasing lease quality for a particular parcels shifts that parcel lower in firms' rankings making it less likely the pair will match. The second variable of primary interest is estimate for the match externality, or *Firm Share*. Table 10a reports a positive relationship (8.092***) suggesting that firms value spatial complementarity as hypothesized in the model section. The estimates for the observable characteristics are also relatively intuitive. The model estimates suggest that all firms value the land size (15.06***) and proximity to infrastructure (5.353*** and 1.237***). Operators have an incrementally greater preference for land size (8.358***), while landmen incrementally prefer leases for parcels located within one kilometer of the drilling site (8.929***).

Landowner value estimates are reported in Table 10b, and the results suggest that landowners value more landowner concessions (3.145***) in contrast to the firms' values. The estimates also suggest that landowners prefer signing leases with larger firms (1.480***). Further, I estimate landowners' heterogeneous preferences for signing leases with landmen over operators that varies with proximity to the future well site. Landowners do not prefer signing leases with operators if they are located nearer to the drilling site (-6.438***), which may be explained by their expectation of future drilling disamenities.

7.3 Model Fit

Table 11 describes how well the estimated match equilibrium from Table 10 captures the observed market structure in the data. Table 11a reports the observed and simulated equilibrium count of leases signed based on the match estimates, and the percent change reports that the simulated model mimics the observed data patterns by signing only 7% fewer leases. The mean HHI values across the observed and simulated leasing patterns are also very similar. Table 11b captures the model fit for a subset of firms. The first two columns compare the firms' counts of leases signed in the data and simulated by the matching model while the last two columns compare the mean shares for those firms. A graphic demonstrating the model fit for the full dataset is included in the Appendix.

8 Counterfactual Analysis

The data reveals that firms sign leases of varying quality, and the estimates from the lease quality model suggest that firms exercise market power on this dimension by signing fewer landowner concessions. The primary counterfactual limits firm competition in lease quality by requiring all firms to offer all feasible landowner concessions.[64] In the reality, pairs of firms and landowners are responsible for adding lease clauses that increase the breadth of environmental testing, limit the use of some chemicals, dampen disruptive traffic or well

[64] Royalty rate is also fixed at 0.25 for the uniform leasing policy.

activity, and delineate the liability for damages occurring over the life of the well. Requiring firms to sign a standard lease that has a specific set of landowner concessions restricts firms from competing for cheap leases, but the restriction also increases firms' costs to lease (and comply with the added restrictions). The market equilibrium under a uniform, or more costly, leasing standard allows one to measure whether, in response, firms sign fewer total leases or employ a more or less spatially concentrated leasing strategy. Further, I approximate changes to welfare for both landowners and firms.

To capture how the lease market internalizes increased contracting costs, I propose a series of incremental increases that culminates to the most costly, uniform leasing standard. In particular, I approximate new equilibrium market structures when (1) all firms must sign a 0.25 royalty rate; (2) costs are only increased for some firms; (3) costs are increased by one required clause for all firms; and (4) all firms must sign a uniformly comprehensive lease. Under uniform leasing, firm j ranks their preferences for landowners based on the values for each parcel, $\Lambda_{firm} + f(X_i, Z_j, \theta; \beta) + \beta share_j^m + \eta_{ij}$, where θ is now fixed for all firms and landowners.[65] I find that firms typically signing leases with fewer landowner concessions in the data will experience a greater increase in cost under uniform leasing, which shifts their spatial leasing behavior or causes them to sign fewer leases altogether. Further, the cost to sign specific lease terms is homogeneous for all firm and landowner pairs, which causes firms to compete more over parcels' observable characteristics and achieve greater spatial agglomeration.

In addition to counterfactual policies that increase costs, I also approximate an equilibrium in which there is no value to signing spatially proximate leases and one that embeds the market power model into the matching framework. In particular, the final policy experiment allows lease quality to depend negatively on market structure using the time invariant, reduced form relationship between lease quality and market structure estimated in the Appendix.

A shortfall of the counterfactual is that the effect of market power on lease quality is not microfounded, and thus, one does not know whether the effects measured by γ in the Section 3 market power models would remain constant with different market structures. Ideally, one would be able to estimate cross-price elasticities for the various contract dimensions; however, embedding a more complex demand system into the one-to-many, NTU match is beyond the current analysis and perhaps an area for future research.

[65] Landowner preferences are represented by ranking firms' offers based on $\Lambda_{parcel} + g(X_i, Z_j, \theta; \alpha) + \xi_{ij}$ for a fixed θ.

8.1 Results

Table 12 reports the changes to market structure (HHI) and to the total count of leases signed by firms.[66] The first restriction to lease quality requires that all firms sign leases agreeing to a 25% royalty, whereas lease royalties observed in the data range from 18% to 25%. The third row of Table 12 reports that there is no measurable change to the market structure when royalty is fixed at a higher rate.

The fourth row of Table 12, *Added Environmental Clause*, increases the restrictiveness by requiring all firms sign a lease with an environmental clause. Requiring the environmental clause increases the costs for some firms, but not all since some firms' leases already included it. In response, the change in concentration is positive (+9.5%) and the total number of leases signed decreases by a small amount.[67] The added costs affect only some firms, which means that previous low quality offers become higher quality offers that induce some landowners to sign leases with the "rising" firms.

The fifth row of Table 12, *Added Clause*, adds a single clause to each potential lease negotiation. As the cost of leasing increases by a single clause, firms agglomerate more (+16.6%) and sign fewer total leases compared to the baseline, but more total leases than *Added Environmental Clause*. Adding to the story from the prior paragraph, a heterogeneous cost increase causes some low quality offers to turn into high quality offers. If this shift occurs among firms with other desirable attributes, then the formerly high quality firms may be pushed out of the market altogether in some regions. Landowners are accepting more of their competitors' offers, and their values for the remaining landowner matches are too low to warrant signing a contract or their offers are undesirable to the remaining landowners.

The sixth row of Table 12 reports the changes under the uniform leasing standard that includes restrictions to noise and additional environmental quality standards, among others. Under uniform leasing restrictions, the market contracts by 21.7% and the market-level concentration increases (+62%). Compared to a single added clause, uniform leasing alters firm behavior more significantly by contracting the total market for leases and causing firms to spatially concentrate their leasing efforts more. Based on this observation, a less

[66] For each counterfactual, I draw a set of match-level shocks, preferences are ranked based on the estimated firm and landowner value functions, firms are matched to landowners via the Deferred Acceptance Algorithm imposing the *firm-optimal* equilibrium, and a new market structure, $share^{m,1}$, results. The counterfactual, equilibrium market structure results when the market structure stabilizes between t and $t-1$ iterations, or $share^{m,t} - share^{m,t-1} = 0$.

[67] The matching model does not differentiate between clause types in a given bundle, weighting the environmental clause the same as the noise clause. However, there would be differential effects across counterfactuals requiring different clauses because each clause is observed with differing frequencies in the data, which means that requiring a less common clause is going to change the market outcomes more than requiring one often already included among the contracting terms.

costly option to uniform leasing may be requiring a set of particularly valuable clauses for landowners.[68]

The final set of counterfactuals, first, devalues spatial agglomeration and, second, allows the quality of leases signed to adjust with the market structure according to the relationships estimated in simple OLS models of lease quality. The second row of Table 12 sets the value of spatial agglomeration to zero, and as expected, market-level concentration decreases (-34.4%). More surprisingly, the market contracts significantly, as well, and the level of contraction is comparable to that under a uniform leasing standard. This relationship suggests that the cost of uniform leasing may be somewhat compensated by the value of spatial agglomeration.

Finally, the two equations in Eq. (9) represent lease quality and firm and landowner values, respectively. Embedding parameter estimates from the reduced form models (reported in the first column of Table 12) into the matching framework, the models converge to new equilibria.

$$\begin{aligned} \hat{\theta}_{ij} &= \hat{\alpha}_0 + \hat{\alpha}_1 share_j^m + \hat{\alpha}_2 X_j \\ v_{ij} &= \Lambda_{firm} + f(X_{i'}, Z_j, \hat{\theta}_{i'j}; \hat{\beta}) + \hat{\beta} share_j^m \\ u_{ij} &= \Lambda_{parcel} + g(X_{i'}, Z_j, \hat{\theta}_{i'j}; \hat{\beta}) \end{aligned} \tag{9}$$

The first, *Lease Quality Adj. (1)*, allows quality to adjust with market structure alone where 10% increase in firm's share results in a reduction to lease quality of -0.300. Allowing for a flexible function of lease quality results in fewer signed leases (-1%) than the baseline and increases to market concentration (27.6%). Since firms view landowner concessions as costly, the negative relationship between lease quality and market structure together results in a decreased cost to lease parcels located in areas where firms have a greater market share.

8.2 Welfare

The welfare measures across counterfactual scenarios are comprised of several pieces including the changes in landowners' values who do and do not sign leases and the changes to firms' values. $\Delta_{i,in}^{base,cf}$ represents the change in welfare to landowners among those that still sign leases, and it reflects the expected profit from signing a lease in the new leasing

[68]This analysis does not differentiate preferences for types of clauses within a bundle; however, joint work with Christopher Timmins seeks to value clauses in a hedonic framework, which may reveal landowners preferences as measured through changes in property values.

unit, Eq. (10), and the value of the change to lease quality.[69]

$$\begin{aligned}
\Delta_{i,in}^{base,cf} &\equiv E[u_{ij}(\Lambda_{parcel}^{in}, X_i, Z_j, \theta_{ij}^{cf}; \hat{\alpha})] - u_{ij}(\Lambda_{parcel}^{base}, X_i, Z_j, \theta_{ij}^{base}; \hat{\alpha}) \\
\text{where } \Lambda_{parcel}^{in} &= 0.05 r_{ij} \frac{a_i}{\sum_{\forall i' \in w^{cf}} a_{i'}} \sum_{t=0}^{T} q_{w,t} p_t^{ng}
\end{aligned} \tag{10}$$

Similarly, $\Delta_{i,out}^{base,cf}$ represents the change in welfare to landowners across those that do not sign leases, and it reflects the loss in expected profit from the old leasing unit, Eq. (11), and the expected lost lease quality from the clauses with private benefits, $\theta_{ij}^{cf,private}$.[70]

$$\begin{aligned}
\Delta_{i,out}^{base,cf} &\equiv E[u_{ij}(\Lambda_{parcel}^{out}, X_i, Z_j, \theta_{ij}^{cf,private}; \hat{\alpha})] - u_{ij}(\Lambda_{parcel}^{base}, X_i, Z_j, \theta_{ij}^{base}; \hat{\alpha}) \\
\text{where } \Lambda_{parcel}^{out} &= 0.05 r_{ij} \frac{a_i}{\sum_{\forall i' \in w^{base}} a_{i'}} \sum_{t=0}^{T} q_{w,t} p_t^{ng}
\end{aligned} \tag{11}$$

Distinguishing between the private and public benefits of leasing acknowledges that even though fewer landowners sign leases in the counterfactual scenarios, they may benefit from more public landowner concessions written into their neighbors' leases, eg. noise and traffic restrictions and environmental testing. I try to account for these positive leasing externalities by approximating welfare where these benefits are still realized by landowners located near to drilling but not negotiating their own lease.

$\Delta_j^{base,cf}$ represents the change in firms' welfare that captures the combined effects of market structure and costs to lease. Tabulating the total acreage leased in the counterfactual, I find that firms still sign leases covering enough acreage to drill, which does not alter their expected profits across baseline and counterfactuals, Λ_{firm}.

$$\Delta_j^{base,cf} \equiv \Lambda_{firm} + E[v'_{ij}(X_i, Z_j, share_j^{cf}, \theta_{ij}^{cf}; \hat{\beta})] - v'_{ij}(X_i, Z_j, share_j^{base}, \theta_{ij}^{base}; \hat{\beta}) \tag{12}$$

Comparing the firm and landowner returns from contracting is tricky because their values are normalized by different expected future royalty payments. However, the split is determined by the royalty rate, and to compute a total change in welfare across both sides of the market, I scale the firms' values based on the mean royalty split, or $\nu = \frac{0.23}{1-0.23}$.

Mean welfare estimates are reported in Table 13, and they capture the differences in mean and median outcomes for landowners signing leases under the counterfactual, landowners no longer signing leases, and firms. The third equation (row) of Table 13 describes the total welfare change for landowners. The most beneficial policy is a single added clause

[69] $\sum_{\forall i' \in w^{cf}} a_{i'}$ reflects the sum of the acreage leased to drill a well under the counterfactual.
[70] $\sum_{\forall i' \in w^{base}} a_{i'}$ reflects the sum of the acreage leased to drill a well in the baseline.

(mean increase of 0.124) even when netting out the additional contracting costs born by firms. Uniform leasing results in a median payoff gain of 0.878 for landowners, which is the greatest landowner gain across policies. The costs of this policy are greatest for firms; and the net welfare changes is roughly zero. Finally, the allowing quality to adjust with market structure results in a total net loss (-0.288) where the greatest costs are incurred by landowners signing lower quality leases, which also reduces the public benefits enjoyed by non-negotiating landowners.

These welfare approximations suggest that the net effect of a uniform leasing policy is negative, and requiring firms to add a single clause with an external benefit for all nearby landowners is the most cost effective strategy. The gains to landowners exceed the costs to firms, and the costs to firms are relatively small compared to the other tested policies. Further, the gains are more widely distributed across landowners as indicated by a comparison of mean to median returns. Weighted percent gains suggest that a uniform lease increases mean returns to landowners by 12% (median, 42%), while a single added clause increases returns by 14% (median 19%), and firms' losses are roughly 68% and 15%, respectively, though the average returns to firms from leasing are at least four times larger than landowner returns. Scaling the firms' costs to sign leases with an additional landowner concession, I find that the policy results in a mean welfare increase of 8%.

9 Conclusion

This paper estimates the effects of spatial concentration on the pecuniary and non-pecuniary contracts and market formation in the context of the oil and natural gas lease market. Modeling lease negotiations is complex because the contracts are multidimensional, of which some features are unobserved, and I observe only the final market assignment. Further, spatial agglomeration directly enters firms' values, which engenders complex, complementary preferences for spatially proximate parcels. Private contracting behavior is modeled as a one-to-many, NTU match where firms sign leases with sets of landowners. In this setting, I find that firms value signing leases for spatially proximate parcels. As a result, I extend the matching framework to allow identification of a model with a specific type of complex, complementary preferences by introducing a set of statistical moments and imposing a set of simplifying assumptions. Through this extension, I am able to estimate the value of spatial agglomeration and cost of more strict contracting in the lease market. Finally, I find that firms exercise market power in the pecuniary and non-pecuniary contracting terms they offer landowners.

Post-estimation, I test the changes to market structure when firms are required to sign leases containing more landowner concessions, which increases their contracting costs. Firms respond to the policies by signing fewer leases, but also by spatially concentrating their leasing efforts more, which may result in faster drilling. Further, back-of-the-envelope welfare approximations suggest that while uniform leasing has a net zero effect for firms and landowners combined, requiring a single clause increases landowner welfare by 12% on average and decreases firm welfare by 15%, which results in a total net welfare gain of roughly 8%.

The current leasing market allows firms to benefit from market concentration on two margins, while landowners with valuable mineral rights pay the cost through worse pecuniary and non-pecuniary contracting terms. My analysis shows that increasing contracting costs for firms does not significantly deter them from leasing (and drilling) even when they are unable to compensate their losses on an unobserved dimension like negotiating lower royalties or bonuses. Further, I find that there are policies in which the gains to landowners outweigh the added costs to firms, leading to an average welfare gain. I would also argue that the implications of these policies exceed the dimensions of my model especially in a market where there is increasing scientific and economic evidence substantiating the potential risks of living near hydraulically fractured wells. Protecting landowners from future disamenities by requiring stricter leasing standards is a potentially low cost mechanism to limit their exposure to drilling risks.

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Table 1: Lease Clause and Bundle Summary Statistics

(a) Primary Terms

	Obs.	Mean	Std.	Min.	Max.
Royalty	176,380	0.231	0.024	0.125	0.284
Term Length (months)	284,797	42.467	11.887	12	60
Bonus	5,752	15,877.61	6,542.64	200	25,000

(b) Auxiliary Clauses

	Mean	Std.	Clause/Bundle	Mean	Std.
Disamenity Bundle	0.085	(0.158)	Legal Bundle	0.081	(0.198)
Environment	0.177	(0.382)	Vertical Pugh	0.105	(0.306)
Noise	0.220	(0.414)	Pugh	0.115	(0.318)
Freshwater	0.016	(0.124)	Insurance/ Indemnity	0.040	(0.197)
Surface Casing	0.005	(0.068)	Records	0.078	(0.268)
Compression Station	0.007	(0.086)	Attorney Fee	0.070	(0.254)
Aesthetic Bundle	0.164	(0.208)	Water Bundle	0.020	(0.072)
Fence	0.370	(0.483)	Freshwater	0.016	(0.124)
Setback	0.134	(0.34)	Disposal Well	0.002	(0.046)
Noise	0.220	(0.414)	Surface Casing	0.005	(0.068)
Rest. Residential Street	0.092	(0.29)	No Water Use	0.003	(0.058)
Storage Tank	0.003	(0.052)	Groundwater	0.076	(0.265)
Surface Use Bundle	0.186	(0.18)	Bads Bundle	0.336	(0.389)
No Surface	0.543	(0.498)	Subsurface Easement	0.463	(0.499)
Surface Restriction	0.031	(0.174)	No Litigation	0.210	(0.407)
All Damage	0.035	(0.183)			
Setback	0.134	(0.340)	Post-Production Cost	0.182	(0.386)
Observations	150,501				

(c) Correlation Matrix

	Royalty	Term (months)	Land Size	Clause
Term (months)	-0.2528			
Land Size	-0.0138	-0.1032		
Clauses	0.2051	-0.3790	-0.0415	
Bonus	0.5969	-0.2617	0.0818	0.5158

Notes: (i) The first panel reports the summary statistics for the primary lease terms including royalties, primary term lengths, or the number of months until the lease expires and the mineral rights revert back to the landowner, and bonuses; (ii) the second panel reports the frequency of individual auxiliary clauses that are accounted for in each bundle type; (iii) all bundles except "bads" are clauses protecting landowners and a large term length is interpreted as worse for landowners; (iv) the primary lease quality analysis uses a sub-sample of 150,501 leases with auxiliary clauses; (v) the correlation matrix demonstrates that the pecuniary and non-pecuniary terms of the lease are positively correlated suggesting landowners may not be trading off additional royalty for fewer clause concessions.

Table 2: Parcel and Firm Summary Statistics

	Obs	Mean	Std.	Min	Max
(a) Firm Characteristics					
Landmen	174,162	0.23	0.42	0	1
Large Operators	174,162	0.30	0.46	0	1
Complaint by Firm	14	1	3.46	0	13
Firm's Tarrant Wells (before 2004)	6	46	69	2	185
Pooling Application (by firm)	761	4.33	8.4	0	24
Field Rule Applications (by firm)	761	0.14	0.35	0	1
18-Month Oil Future Price	131	80.36	24.61	30.42	155.76
18-Month Natural Gas Future Price	131	7.31	2.63	3.5	13.28
Pred. Oil Price Volatility	131	1.01	0.17	0.68	1.58
Pred. Natural Gas Price Volatility	131	0.79	0.08	0.64	0.94
(b) Parcel Characteristics					
Land Size (sqft)	174,162	10,811.62	9,005.925	1,000	87,556
Avg. Appraisal Value	163,519	112,811.9	86,421.23	0	2,810,455
Near Well (km)	174,162	1.072	0.517	0.211	3.999
Near Pipeline (km)	162,569	1.204	0.876	0.000	4.981
Expected Parcel Profit (annualized)	173,759	140.04	245.14	0.002	7,958.41

Notes: (i) The first panel reports the summary statistics parcel characteristics; (ii) the second panel summarizes the firm characteristics (iii) summarized application data is calculated for each firm, year, and month; (iv) summarized price data is calculated for each year and month in the data.

Table 3: Moments and Identification

Joint Distribution	$\frac{1}{N}\sum_{\substack{i\in\mu(j)\\ \forall j\in J}} X_{ij}Z_{ij}$
Attribute Covariance	$\frac{1}{N-1}\sum_{\substack{i\in\mu(j)\\ \forall j\in J}} (X_{ij}-\bar{X})(Z_{ij}-\bar{Z})$
Firm-level Moments	
Within-Firm Joint Dist.	$\frac{1}{N_j}\sum_{i\in\mu(j)} X_{ij}Z_{ij}$
Within-Firm Variance	$\frac{1}{N_j}\sum_{i\in\mu(j)} (X_{ij}-\sum_{i'\in\mu(j)} X_{i'j})^2$
Within-Firm Covariance	$\frac{1}{N_j-1}\sum_{i\in\mu(j)} (X_{ij}-\frac{1}{N_j}\sum_{i'\in\mu(j)} X_{i'j})(Z_{ij}-\frac{1}{N_j}\sum_{i'\in\mu(j)} Z_{i'j})$
Market-level Moments	
Within-Market Joint Dist.	$\frac{1}{N^m}\sum_{\substack{i\in\mu(j)^m\\ \forall j\in J}} X_{ij}Z_{ij}$
Within-Market Variance	$\frac{1}{N^m}\sum_{\substack{i\in\mu(j)^m\\ \forall j\in J}}(X_{ij}-\frac{1}{N^m_j}\sum_{\substack{i'\in\mu(j)^m\\ \forall j\in J}} X_{i'j})^2$
Within-Market Covariance	$\frac{1}{N^m-1}\sum_{\substack{i\in\mu(j)^m\\ \forall j\in J}} (X_{ij}-\frac{1}{N^m}\sum_{\substack{i'\in\mu(j)^m\\ \forall j\in J}} X_{i'j})(Z_{ij}-\frac{1}{N^m}\sum_{\substack{i'\in\mu(j)^m\\ \forall j\in J}} Z_{i'j})$
Within-Firm & Market Var.	$\frac{1}{N^m_j}\sum_{\substack{i\in\mu(j)^m\\ \forall j\in J}} (X_{ij}-\frac{1}{N^m_j}\sum_{i'\in\mu(j)^m} X_{i'j})^2$
Market Structure Moments	
Market structure	$share^{0,m}_j-\widehat{share}^m_j$
Joint Dist. Landowner Att.	$\frac{1}{J}\sum_{\forall j\in J}\widehat{share}^m_j(\frac{1}{N^m_j}\sum_{i\in\mu(j)^m} X_{ij})$
Joint Dist. Firm Att.	$\frac{1}{J}\sum_{\forall j\in J}\widehat{share}^m_j(\frac{1}{N^m_j}\sum_{i\in\mu(j)^m} Z_{ij})$

Notes: (i) N is the count of matched landowners across all markets, N^m is the count of matched landowners located in market m, and N^m_j is the count of matched landowners to a firm j in market m; ii) $\mu(j)^m$ denotes the partition of landowners matched to firm j in market m, and $\mu(j)$ denotes the partition of landowners matched to firm j across all markets; iii) $\bar{X}$ and $\bar{Z}$ denote the mean attribute values for landowner and firm characteristics among pairs that match; iv) Each moment, except the market structure moments, is calculated for each k observable variable, and the notation is simplified by excluding a superscript k.

Table 4: Geographic Market Characteristics

	Obs	Mean	Std.	Min	Max
Leases in market	394	442.04	614.10	1	3,915
Firm Share	9,098	0.13	0.22	0	1

Notes: (i) Table 4 summarizes the market characteristics; (ii) *Lease in market* describes the count of individuals parcels in geographic markets across Tarrant County and *Firm Share* summarizes the primary measure of market structure; (iii) a figure in the appendix graphically demonstrates variation in market structure across firms.

Table 5: Market Power Estimates - Primary Terms

	Royalty	Royalty* (Land/Total)	Term (month)	Post Prod. Cost
Lease Share (Firm)	-0.011***	-0.824***	8.325***	-0.077**
	(0.002)	(0.121)	(1.179)	(0.032)
Land size (1e-2 sqft)	0.000***		-0.045***	-0.000*
	(0.000)		(0.009)	(0.000)
Dist. To WP (Inv.)	-0.002	-0.427**	0.551	-0.092***
	(0.002)	(0.171)	(1.075)	(0.024)
18-Mon. Oil Future	0.033***	-0.736***	-3.549	0.161
	(0.005)	(0.260)	(2.795)	(0.105)
18-Mon. NG Future	-0.165***	19.778***	-7.012	0.044
	(0.057)	(3.845)	(31.940)	(0.800)
Pred. Fut. Oil Vol.	0.009**	1.144***	-6.091***	0.157
	(0.004)	(0.300)	(2.349)	(0.133)
Pred. Fut. NG Vol.	-0.074***	0.730	18.436**	-0.322
	(0.014)	(1.178)	(7.703)	(0.306)
Constant	0.243***	8.111***	23.292***	0.277
	(0.014)	(1.790)	(6.236)	(0.294)
Observations	148,986	148,988	149,467	149,640
R-squared	0.366	0.049	0.156	0.277
Clustered Std. Err.	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: (i) Each column represents a separate OLS specification regressing lease quality on observable parcel attributes; (ii) standard errors are clustered by geographic market.

Table 6: Market Power Estimates - Primary Terms

	Royalty	Royalty* (Land/Total)	Term (month)	Post Prod. Cost
Lease Share (Firm)	-0.017*	-5.606***	35.978***	-0.771***
	(0.010)	(1.634)	(10.195)	(0.258)
Land size (1e-2 sqft)	0.000**		-0.004	-0.001***
	(0.000)		(0.019)	(0.000)
Dist. To WP (Inv.)	-0.003	-0.800***	2.787*	-0.148***
	(0.002)	(0.261)	(1.519)	(0.038)
18-Mon. Oil Future	0.031***	-1.958***	3.674	-0.021
	(0.006)	(0.634)	(4.976)	(0.146)
18-Mon. NG Future	-0.158***	24.915***	-40.414	0.878
	(0.059)	(5.382)	(41.314)	(0.963)
Pred. Fut. Oil Vol.	0.008**	0.788*	-4.238	0.111
	(0.004)	(0.453)	(3.000)	(0.141)
Pred. Fut. NG Vol.	-0.067***	5.761***	-10.616	0.405
	(0.017)	(2.120)	(14.281)	(0.417)
Constant	0.245***	9.095***	16.574*	0.448
	(0.014)	(1.828)	(8.778)	(0.349)
Hansen Overid P	0.385	0.035	0.091	0.938
End T	0.641	3.761	-4.969	2.928
First Stage				
Pre-2004, near prod.	0.015***	0.014***	0.015***	0.015***
	(0.005)	(0.005)	(0.005)	(0.005)
Pooling Approved	-0.007***	-0.007***	-0.006***	-0.006***
	(0.002)	(0.002)	(0.002)	(0.002)
1st stage R-squared	0.141	0.138	0.141	0.141
1st stage F-stat	83.635	70.092	83.161	83.372
Observations	148,986	148,988	149,467	149,640
Clustered Std. Err.	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: (i) Each column represents a separate 2SLS specification regressing lease quality on observable parcel attributes; (ii) 2SLS instruments Firm Cumulative Share with a measure of a firm's pre-2004, nearby well count and the count of pooling and field rule changes approved by the TRC across Texas; (iii) standard errors are clustered by geographic market; (iv) *Hansen Overidentification* tests the null hypothesis that the over-identifying restrictions are valid, and the reported probability statistics suggest that the over-identifying restriction validity cannot be rejected at the 90% level lending confidence to the instrument choices; (v) *Wu-Hausman Endogeneity* tests the null hypothesis that the first-stage residuals are correlated with the outcome variable, suggesting an endogeneity problem, and the *End T-stats* suggest that market concentration is likely endogenous; (vi) first stage results report only the instrumental variable estimates though each first stage model is estimated using the full set of control variables.

Table 7: Lease Quality Estimates - Auxiliary Terms

	Full Set	"Bads"	Disamenity	Aesthetics	Surface	Legal
			(a) OLS			
Lease Share (Firm)	-0.033**	0.044*	-0.044***	-0.032**	-0.020*	-0.037**
	(0.014)	(0.025)	(0.011)	(0.015)	(0.011)	(0.019)
Land size (1e-2 sqft)	-0.000	-0.000	0.000	-0.000	-0.001***	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Dist. To WP (Inv.)	-0.033***	0.140***	-0.024***	-0.022*	0.010	-0.048***
	(0.011)	(0.022)	(0.009)	(0.013)	(0.012)	(0.014)
Constant	0.098***	0.017	0.171***	0.232***	0.063***	0.055***
	(0.014)	(0.031)	(0.014)	(0.022)	(0.015)	(0.020)
Observations	149,663	149,663	149,663	149,663	149,663	149,663
R-squared	0.270	0.203	0.362	0.276	0.300	0.275
			(b) 2SLS			
Lease Share (Firm)	-0.456***	2.070***	-0.666***	-0.430**	0.257	-0.564**
	(0.161)	(0.575)	(0.199)	(0.169)	(0.177)	(0.238)
Land size (1e-2 sqft)	-0.001***	0.002***	-0.001***	-0.001***	-0.000	-0.001***
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Dist. To WP (Inv.)	-0.070***	0.316***	-0.078***	-0.057**	0.034*	-0.094***
	(0.023)	(0.082)	(0.027)	(0.025)	(0.019)	(0.029)
Constant	0.519***	-2.000***	0.790***	0.627***	-0.212	0.580**
	(0.159)	(0.574)	(0.198)	(0.168)	(0.175)	(0.235)
1st stage F-stat	63.672	289.156	83.754	152.41	337.641	15.275
Hansen Overid P	0.17	0.173	0.066	0.12	0.138	0.251
End T	3.369	-11.239	4.697	2.433	-1.891	2.943
Observations	149,663	149,663	149,663	149,663	149,663	149,663
Clustered Std. Err.	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
First Stage						
Pre-2004, near op. prod.		0.017***				
		(0.005)				
Pooling Approved		-0.006***				
		(0.002)				
Observations		149,663				
1st stage R-squared		0.123				
1st stage F-stat		86.739				

Notes: (i) Each column represents a separate 2SLS specification regressing lease quality on observable parcel attributes; (ii) 2SLS instruments Firm Cumulative Share with a measure of a firm's pre-2004, nearby well count and the count of pooling and field rule changes approved by the TRC across Texas; (iii) standard errors are clustered by geographic market; (iv) *Hansen Overidentification* tests the null hypothesis that the over-identifying restrictions are valid, and the reported probability statistics suggest that the over-identifying restriction validity cannot be rejected at the 90% level lending confidence to the instrument choices; (v) *Wu-Hausman Endogeneity* tests the null hypothesis that the first-stage residuals are correlated with the outcome variable, suggesting an endogeneity problem, and the *End T-stats* suggest that market concentration is likely endogenous; (vi) first stage results report only the instrumental variable estimates though each first stage model is estimated using the full set of control variables.

Table 8: Assortativity

(a) Firm Assortativity

	Exp. Profit	Lease Qual.	Firm Compl.	Firm Well Ct.	Dist. Well (LM)	Dist. Well (Op)
Parcels/Market	-0.502***	-0.25***	0.173***	-0.02***	0.003***	0.002**
	(0.009)	(0.008)	(0.002)	(0.003)	(0.000)	(0.001)
Appraisal Value	-0.359***	0.460***	-0.26***	2.112***	0.020***	0.025***
	(0.083)	(0.074)	(0.023)	(0.032)	(0.004)	(0.007)
Land size (sqft)	1.580***	0.011	-0.08***	-0.09***	-0.004***	-0.005*
	(0.035)	(0.032)	(0.009)	(0.013)	(0.002)	(0.003)
Within 1km of Well	-0.003	-0.19***	-0.08***	-0.09***	-0.001*	0.000
	(0.007)	(0.006)	(0.002)	(0.003)	(0.000)	(0.001)
Dist. To Pipe (Inv.)	0.628***	-0.214	-0.015	-0.011	-0.001	-0.002
	(0.240)	(0.220)	(0.064)	(0.090)	(0.010)	(0.018)
Lease Quality	-0.041***		0.202***	-0.46***	0.002***	0.009***
	(0.008)		(0.002)	(0.004)	(0.000)	(0.001)
Land size (sqft) LM	-0.251***	-0.99***	-0.08***	-0.52***	0.011***	0.005
	(0.053)	(0.049)	(0.014)	(0.020)	(0.002)	(0.004)
Land size (sqft) OP	-0.104***	-0.29***	-0.006	0.400***	0.000	0.027***
	(0.040)	(0.036)	(0.011)	(0.015)	(0.002)	(0.003)
Firm Share	-0.069***	-0.58***	-0.03***	-0.19***	-0.000	0.013***
	(0.007)	(0.006)	(0.002)	(0.003)	(0.000)	(0.001)
Expected future profit		2.094***	0.574***	0.283***	0.172***	0.409***
		(0.182)	(0.053)	(0.075)	(0.009)	(0.015)
Observations	250,210	245,203	250,210	250,210	250,210	250,210
R-squared	0.043	0.370	0.160	0.422	0.166	0.181

(b) Landowner Assortativity

	Exp. Profit	Lease Qual.	App. Value	Land Size	1km Well	Firm Share
Firm Complaints (Pre-2004)	-0.013*	-0.12***	-0.00***	-0.02***	-0.004	-0.01***
	(0.008)	(0.007)	(0.000)	(0.001)	(0.003)	(0.002)
Firm Barnett Ct. (Pre-2004)	-0.01**	-1.08***	0.007***	0.016***	-0.005***	-0.05***
	(0.005)	(0.004)	(0.000)	(0.001)	(0.002)	(0.001)
Lease Quality	-0.013**		0.014***	0.044***	0.064***	-0.137***
	(0.005)		(0.000)	(0.001)	(0.003)	(0.003)
Expected Future Profit		-2.451***	0.068***	2.280***	1.539***	0.096
		(0.202)	(0.005)	(0.024)	(0.076)	(0.060)
Observations	250,210	245,203	250,210	250,210	250,210	250,210
R-squared	0.005	0.282	0.555	0.499	0.748	0.556

Notes: (i) Each column for both panels is an OLS regression describing assortativity; (i) the dependent variables for each column are the firm or landowner characteristics; (ii) the first panel reports estimates of firms' assortativity across landowner characteristics (columns); (iii) the second panel reports estimates of landowners' assortativity across firm characteristics; (iv) the data used to run the OLS regressions are normalized to lie between zero and one to mimic the scaling used to estimate the matching model; (vi) LM, landman, and OP, operator preferences (estimated with proximity interactions).

Table 9: Spatial Complements: Time to Permit & Produce

	Time to Permit	Time To Produce	Time Between
Firm Share	-1.319***	-5.575***	-19.709***
	(0.135)	(0.143)	(0.579)
Constant	46.515***	58.780***	18.688***
	(0.823)	(0.871)	(3.939)
Observations	217,781	215,515	288,089
Firm, Year FE	Yes	Yes	Yes
R-squared	0.251	0.369	0.048

Notes: (i) Each column is a different model specification and the first and second dependent variables are the months until the eventual well is permitted and producing, respectively; (ii) the third column's dependent variable describes the days between the current lease and the last one signed; (iii) sample sizes differ across specifications because not all leases are eventually converted to a drilling permit (comparing the first and last columns) and not all permits result in drilled wells (comparing the first two columns).

Table 10: Matching Model Estimates

	Firm Type Pref.	Estimate	Std. Errors
(a) Firm Values			
Appraised Value		1.807	(0.086)
Parcels in Market		0.892	(0.066)
Land size (sqft)		15.06	(0.087)
Dist. To Pipeline (Inv. km)		5.353	(0.088)
Within 1km of Well		1.237	(0.074)
Land size (sqft)	Landman	-2.535	(0.088)
Dist. To Pipeline (Inv. km)	Landman	8.929	(0.080)
Within 1km of Well	Landman	-0.573	(0.080)
Land size (sqft)	Operator	8.358	(0.107)
Dist. To Pipeline (Inv. km)	Operator	-5.313	(0.074)
Within 1km of Well	Operator	-0.307	(0.090)
Lease Quality		-5.825	(0.080)
Firm Share		8.092	(0.101)
(b) Parcel Values			
Firm Barnett Well Count (Pre-2004)		1.480	(0.085)
Firm Complaints (Pre-2004)		0.019	(0.095)
Well Dist. (Inv. km)	Landman	1.835	(0.095)
Well Dist. (Inv. km)	Operator	-6.438	(0.099)
Lease Quality		3.145	(0.107)
J-Statistic	0.0014	Obs.	58,663

Notes: (i) The first panel reports the firms' parameter estimates; (ii) the second panel reports the landowners' parameter estimates; (iii) the *Lease Quality* terms measures the negative (positive) effect of additional landowner concessions written into leases signed by firms (landowners); (iv) the *Firm Share* term measures the positive effect of geographic complementarity on firms' values, or the effect of the match externality.

Table 11: Model Fit

(a) Lease Count & HHI (Mean)

	Lease Count	Pct. Change	HHI	Pct. Change
Observed	58663		0.425	
Simulated	54557	-0.070	0.394 (0.248)	-0.074

(b) Lease Count & Share (Mean)

	Obs. Count	Sim. Count	Obs. Share	Sim. Share
Smallfirm	2743	2681	0.1065	0.0834
Carrizo	4634	4525	0.0544	0.0526
Chesapeake	11383	11383	0.2162	0.2024
Dale	16827	15088	0.2489	0.2220
Paloma Barnett	4847	4005	0.0464	0.0419
Xto	3940	3940	0.1249	0.0912

Notes: (i) The top panel compares the count of leases observed in the data to the count simulated using the matching equilibrium estimated and reported in Table 10, and it compares the mean HHI; (ii) the bottom panel evaluates the model fit by firm comparing the observed to simulated lease counts and firm shares.

Table 12: Counterfactual Outcomes: Market Structure

	Coef. (St.Dev.)	HHI (St.Dev.)	Pct. Change	Lease Count	Pct. Change
Baseline (Simulated)		0.394 (0.248)		54557	
No Value to Spatial Concent.		0.258 (0.145)	-0.344	43513	-0.202
Royalty 25%		0.394 (0.248)	0.000	54557	0.000
Added Environmental Clause		0.431 (0.237)	0.095	54026	-0.01
Added Clause		0.459 (0.265)	0.166	54310	-0.005
Uniform Leasing		0.637 (0.298)	0.618	42708	-0.217
Lease Quality Adj. (1)		0.502 (0.252)	0.276	54080	-0.009
Firm Share	-0.300 (0.019)				
Constant	0.594 (0.002)				
Lease Quality Adj. (2)		0.472 (0.243)	0.200	54207	-0.006
Firm Share	-0.318 (0.004)				
Land size (sqft)	0.039 (0.004)				
Constant	0.548 (0.001)				
Observed		0.425 (0.183)		58663	

Notes: (i) The columns in Table 12 report the HHI measures of concentration and counts of leases signed along with the resulting changes to these measures across policy experiments; (ii) *Uniform Leasing* requires all firms to include all landowner concessions, *Added Env. Clause* requires environmental testing, and *Added Clause* increases the number of clauses in all leases by one; (iii) *Lease Quality Adj.* allows the quality to change with the changes to market structure as the model converges to a new equilibrium using estimates (reported) from simple OLS regressions.

Table 13: Counterfactual Outcomes: Mean Welfare

	Uniform Leasing	Added Env. Clause	Added Clause	Lease Qual. Adj. (1)
Landowners Signing Leases	*Mean (Std.Err.)*			
$\Delta_{i,in}^{base,cf}$	1.083 (0.857)	-0.021 (0.46)	0.415 (0.13)	-0.119 (0.38)
Median	1.289	-0.014	0.433	-0.059
Landowners Not Signing Leases (loss)				
$\Delta_{i,out}^{base,cf}$	1.171 (1.50)	0.11 (0.4)	0.154 (0.26)	0.274 (0.43)
	0.446	0.011	0.041	0.106
Landowners Change				
$\Delta_{i,in}^{base,cf} - \Delta_{i,out}^{base,cf}$	-0.089 (2.287)	-0.131 (0.68)	0.262 (0.30)	-0.392 (0.61)
	0.878	-0.096	0.373	-0.228
Firms				
$\Delta_{j}^{base,cf}$	-3.481 (1.684)	0.269 (1.76)	-0.785 (0.50)	-0.083 (1.08)
	-3.497	-0.015	-0.779	-0.085
Total Change				
$\nu\Delta_{j}^{base,cf} + \Delta_{i,in}^{base,cf} - \Delta_{i,out}^{base,cf}$	-0.90 (0.649)	0.051 (0.50)	0.124 (0.51)	-0.288 (0.06)
	-0.060	0.008	0.185	-0.184

Notes: (i) Table 13 describes the mean (std) and median welfare changes across three policy experiments; (ii) the benefits attributed to landowners that sign better leases outweigh the losses from landowners not signing leases in each policy experiment ($\Delta_{i,in}^{base,cf} - \Delta_{i,out}^{base,cf}$).