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

Ashley Vissing[a]

Abstract

In a two-sided market with private contracting, what are the costs and benefits of market power? I study this question in the context of firms negotiating leases for natural gas mineral rights with landowners. Firms benefit from signing contracts that are geographically proximate, 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 concentrated leases. The model estimates imply there are substantial benefits to market power 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.

[1]Thank you to my advisor, Christopher Timmins, for his guidance, support, and encouragement. Thank you also to my committee members, James Roberts, Curtis Taylor, Modibo Sidibe, and Richard Newell. Thank you also to Tom Milldrige at Duke Computing and Ryke Longest at Duke Law School for their helpful discussion and advice. This paper has also benefited from comments from and discussions with Stéphane Bonhomme, Koichiro Ito, Michael Greenstone, Ryan Kellogg, Thomas Covert, Mar Reguant, Jeremy Fox, and participants the IO/Public Lunch Seminar at Duke University, the EPIC Lunch and Junior Faculty Seminars at the University of Chicago, and the Advances in Environmental Economics Conference at Arizona State University. Thank you to personnel at the Texas Railroad Commission, the Tarrant County Appraiser Office, and DrillingInfo for guidance in collecting the well and housing/parcel data. This research is supported by a National Science Foundation Grant #1559481. Any remaining errors are my own.

[a]University of Chicago, Saieh Hall for Economics 364, 1126 E. 59th St. Chicago, IL 60637, abvissing@uchicago.edu.

1 Introduction

What are the distributional consequences of market power on privately negotiated contracts? Whether market power 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 power 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 dis-amenities, 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 dis-amenities increase total welfare across firms and landowners, and I use my findings to support a uniform leasing standard that mandates more 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 power and the prevalence of landowner concessions using an instrumental variable model. I find that greater market power (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 when there are complementarities from owning the rights to contiguous clusters of land? 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 power from signing geographically clustered 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 power 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 power because the shale oil and natural gas industry comprises a significant portion of all onshore oil and natural gas development in the United States, 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, I conduct policy analyses that impose leases include more landowner concessions. The policy analyses are potentially important because they are not currently implemented in the industry[1] and represent a low cost

[1]There are a few tangential policies. First, existing regulations stipulate that leases include surface

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 shares and lease outcomes by instrumenting market shares with measures of firms' nearby, pre-2004 well production activity and their regulatory prowess. After 2004, firms began profiting from leasing minerals and drilling wells in densely populated regions overlaying tight-shale formations, characteristics of my study region, in response to technological innovation. The first instrument relies on pre-2004 drilling behavior, which occurred, on average, three years beforehand and in a nearby, geographic market, not affecting the specific contracting terms except through the effect on lease market structure. The second instrument, regulatory prowess, aids firms that need to form irregular drilling units, which is more common in regions comprised of densely populated neighborhoods. Yet approvals granted by the state regulator are likely not correlated with private landowner interactions and lease outcomes, especially since lease outcomes govern different aspects of firms' drilling and producing behavior. 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 power are shared across firms

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.

[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, 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. 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 and landowners that arise from bilateral decision-making.[5] Further, firms' and landowners' choice sets 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 endogenous to how firms sign leases with sets of landowners. It 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 stable equilibrium existence and multiplicity, 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 pairwise stable equilibrium. Pairwise stability, in the lease setting, 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. Valuing lease market share means that any deviating pair must consider, not only

[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, TU match with complements.

their own sets of outside options,[10] but also all other agents' responses to their deviation since geographic market shares are measures of the total market assignment across all active firms and landowners. Assuming that firms are myopic in their 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. 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 power 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]

The paper contributes to the empirical matching literature by adding a match exter-

[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 3.2, 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.

nality 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.

Topically, this paper studies the private natural gas leasing market and contributes to the

[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).

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, which are followed by the exposition of the estimated lease negotiation model in section 3 and estimation strategy in section 4. The data are described in section 5 and estimates of the reduced form models are reported in section 6. Section 7 reports the estimates of the one-to-many matching model, 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

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.

Hydraulic fracturing involves injecting fluids, primarily water mixed with other chemicals, at high pressures into the drilled well such that the rock cracks and produces artificial fissures throughout the shale strata. The fracturing fluid contains proppants, like quartz sand grains,

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

that keep the fissures open well after the fracturing fluid has returned to the wellhead once the pressure is released. Horizontal drilling techniques with laterals measuring roughly 3000 to 5000 feet ensure that large quantities of shale are exposed to the artificial stimulation generated by hydraulic fracturing while boring fewer holes to drill wells (Zeik (2009); King (2011)). Further, the fracturing stages can take place iteratively or all at once, 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 regulatory mechanisms, protecting landowners' properties and aesthetics and mitigating their exposure to drilling dis-amenities during the well development phases. The TRC does not regulate aspects of the drilling process like excessive noise and traffic, legal aspects of mineral

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

ownership and transference, and use of certain equipment (e.g. compression stations). They do not require pre- water and soil testing,[20] and they have more 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 require environmental testing, limit noise and traffic from drilling activity, restrict which chemicals can be used to fracture a well, and clearly delineate legal responsibilities across grantors and grantees, among other concession types.

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 estimating the separate firm and landowner values for these private contracts designed to transfer mineral rights for the purpose drilling, restrict firm behavior, and protect landowners from drilling dis-amenities. Additional legal and institutional leasing details can be found in Timmins and Vissing (2015).

3 Model

The following section describes the two-sided, private mineral leasing market as a one-to-many match and assuming non-transferable utility (NTU). The model objective is to value the costs and benefits of market power in the private leasing market across firms and landowners by estimating their separate preferences, which is feasible by assuming NTU. The presented model differs from the existing literature by estimating a large-scale, one-to-many match with a match externality that induces complementary preferences. The following sections frame the private leasing market as a one-to-many match, introduce the components of firms' and landowners' value functions, and describe the equilibrium concept underlying the estimation method.

3.1 Spatial Complementarity

The two-sides of the private leasing market are comprised of landowners and firms where a single firm is observed signing sets of leases with many landowners. The final matched firm and landowner pairs are the result of bilateral agreement. In particular, before drilling a well and producing oil and natural gas for sale, firms amass the legal rights to the mineral estates

[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

from which they want to extract, which may require hundreds of private negotiations in urban areas. In the model, each firm decides where across Tarrant County they want to sign leases by ranking the potential parcels according to observable parcel characteristics, the share of leases signed in that geographic region (or the market structure measure), contract costs, and an unobserved, match-level shock. Each signed lease represents a temporary transfer of the mineral estate from the landowner to the firm, thereby allowing the firm to drill for and extract oil or natural gas. Valuable parcel characteristics include the size of the parcel, proximity to pipelines or future drilling sites,[22] and the expected future profits from drilling a well. Leasing decisions are bilateral in the sense that firms extend offers to landowners and landowners, reciprocally, can accept or reject the offer depending on the landowners' preferences over all received offers. The landowners' decisions to accept offers depend on their ranked preferences comprised of the values for firm attributes, expected future profit from a drilled well, landowner concessions, and an unobserved, match-level shock.

Firm and landowner preferences for matches are ranked using value functions comprised of observed and unobserved characteristics according to the pure characteristics model of Berry and Pakes (2007). Assuming NTU necessitates specifying two distinct utility functions representing firm and landowner preferences. The transfers implied by the observed firm and landowner negotiations are embedded in the specified utilities through terms that characterize the expected future profits split between firms and landowners from royalties and through the unobserved, match-level shocks that capture bonus payments. Fixing expected royalty profits would be problematic if royalties are endogenous to market structure. However, an instrumental variable model relating market structure to royalty rates reveals an insignificant relationship.[23,24]

Equations in Eq. (1) capture the firm j's and landowner i's values for matches in the data through v_{ij} and u_{ij}, respectively. The pecuniary and non-pecuniary characteristics enter firms' value function through $f(X_i, Z_j, \theta_{ij}; \beta)$ that measures the effects of parcel (X_i) and firm (Z_j) characteristics in addition to the lease contract value, θ_{ij}. Similarly, landowners' values are determined by the observables through $g(X_i, Z_j, \theta_{ij}; \alpha)$, and these values underly landowners' preference rankings across firms' lease offers. Firms' and landowners' values also include unobservable, match-level shocks through the additively separable terms 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

[22] Due to institutional factors and geographic limitations of leasing and drilling in urban regions, assuming wellpad location is exogenous is more reasonable.

[23] This estimate is formally presented in Section 6 and Table 5.

[24] A small bonus sample is a limitation of the data. The estimated model circumvents this issue by treating bonuses as part of the unobserved negotiation shocks.

attributes of the lease or negotiation process known to firms and landowners that sign the lease rendering the particular negotiation more or less attractive to the two parties. These unobservable attributes might include bonus payments, a particularly effective sales pitch or strong negotiation skills, or a parcel unencumbered by trees, among other examples. Inclusion ensures that preference rankings for both firms and landowners are strict and that the equilibrium found by the model is unique.

Firms value spatial agglomeration in leasing activity directly through their value functions. In addition to firms' preferences for observable match-level characteristics, firms' values vary with the total market assignment by including a measure of their geographic market share, $share_j^m$, or the match externality, which is defined for each firm j and geographic market m.

$$\begin{aligned} v_{ij} &= f(X_i, Z_j, \theta_{ij}; \beta) + \beta share_j^m + \eta_{ij} \\ u_{ij} &= g(X_i, Z_j, \theta_{ij}; \alpha) + \xi_{ij} \end{aligned} \tag{1}$$

Firms value spatial agglomeration because it allows them to more easily apply for a drilling permit and profit from oil and natural gas production.[25] Directly valuing geographic market share induces complementarity in firms' preferences for sets of proximate leases and is the pivot point from the existing empirical NTU literature.

Finally, Firms have a cap on the total number of leases they are able to sign across Tarrant County, which is denoted $\bar{q}_j$, and this constraint reflects each firms' total capacity for lease negotiations that is observed in the data. In practice, firms' lease constraints ($\bar{q}_j$) are exogenously given, and firms in the model are free to sign up to the same number of leases as observed in the data.

3.2 Myopic Estimation Function

Firms' negotiation values, which include the direct effect of the market share match externality, depend on both the payoff from a specific pairing and the entire assignment of matches. Any deviating 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 since firm preferences are defined over assignment through $share_j^m$ rather than being simply defined over matches. 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

[25]The relationship between market structure and "time to drill" in the data is addressed directly in Section 7.1 and Table 8, 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.

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.[26] A myopic estimation function maps the set of lease choices, or all potential lease pairings, to the estimated market shares observed for each firm across all geographic markets, or $\mathcal{F}_j : \cup_{i \in \mathcal{N}} \mu_j(i) \rightarrow \mathbb{R}_+$, where $\mu_j(i)$ describes a match between firm j and landowner i.[27]

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 $\bar{q}_j$ in the model section.

3.3 Pairwise Stability

Based on the value functions described in Eq. (1) 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. Leases that are offered and accepted across the two sides of the market are modeled as a series of matches mapping from the sets of landowners to firms, where a match between firm $j \in \mathcal{J}$ and landowner $i \in \mathcal{N}$ is denoted $\mu_j(i) : \mathcal{N} \rightarrow \mathcal{J} \cup \{0\}$.[28] A particular match between j and i is predicated on the agreed upon contract value denoted θ_{ij}. The set of contract values and matches between the two sides of the leasing market are assumed to satisfy pairwise stability.

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*:

[26] 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).

[27] 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.

[28] $\{0\}$ denotes not signing a lease.

(a) Landowners: $u_{ij} \geq 0$.

(b) Firms: $\nexists\, \tilde{\theta}_j \subset \mathcal{D}_j$ s.t. $V_j(\tilde{\theta}_j, share_j^{m*}) \geq V_j(\theta_j^*, share_j^{m*})$, $\sum\limits_{i \in \mu_j(i)} \mu_j(i) \leq q_j$.

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 to 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 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, the stability condition must hold for the estimated market assignment, $share_j^{m*}$.

In general, a pairwise stable equilibrium is not guaranteed to exist and, if it does, it is not guaranteed to be unique. Existence is a particularly thorny issue in the presence of complementary preferences. In particular, including firm share allows the preference for a single match to depend on the firms' 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.[29] 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.

3.4 Heterogeneous Preferences

Both sides of the market allow for heterogenous preferences, and firms' preferences for some landowner attributes vary across large operators and landmen, or firms that do not drill wells and participate in the leasing market as appropriators of mineral rights.[30] In particular, the firms' preferences for the size of the parcel and measures of proximity to drilling infrastructure vary across the two firm types, which are two exogenous variables entering firms' value functions. These observable landowner attributes are excluded from

[29]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.

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

the observable attributes characterizing landowner values on the other side of the market. Parcel size and proximity measures are valuable to firms expecting to drill a well because these measures affect the cost to drill either by lessening the time to permitting[31] or reducing infrastructure costs. One might expect incentives across firm types to differ since operators' goals are to drill, while landmen are motivated by the implied future royalties from any well drilled on or near their owned minerals.

3.5 Lease Quality

The model of lease negotiation suggests that firms value spatial complementarity across the sets of leases they negotiate with landowners located in the same geographic region. As a consequence, mineral rights are more valuable, in concert with the other observable characteristics of the parcel, when they are located in regions where firms own a large share of the mineral rights. This section presents a simple model capturing the relationship between market structure and lease quality to better understand whether firms exercise market power in pecuniary and non-pecuniary contract terms.

As firms amass more leases in a geographic region, there are fewer competing firms since the property rights are rivalrous. As a consequence, the dominant firm may be able to offer terms that are less desirable to landowners knowing that landowners are receiving fewer offers from their competitors. A competitive equilibrium in the matching framework maximizes the total surplus, which suggests that lease offers result in high quality firms matching with high quality landowners. In the current setting, the landowner's value to a given firm increases with that firm's market share, and the firm extracts additional rent by exercising market power in contract terms.

Based on this setup, lease quality is determined by the firm's and landowner's observable characteristics ($q(X_i, Z_j; \delta)$) and the market structure ($share_j^m$). Since a greater market share increases the value of individual parcels, we might assume that firms valuing those parcels more would offer the landowners better contracting terms as proposed in Eq. (2) for $\gamma > 0$.

$$\begin{aligned} &\theta_{ij} = q(X_i, Z_j; \delta) + \gamma share_j^m \\ &\text{where } \theta_{ij}(share_j) \geq \theta_{ij}(share_j') \text{ if } share_j \geq share_j' \end{aligned} \tag{2}$$

However, when firms exercise market power, they extend worse contracting terms to landowners, $\gamma < 0$. The simple OLS and 2SLS models are designed to test for the prevalence of market

[31] A larger parcel may lessen the time to permitting by reducing the total number of negotiations comprising the remainder of the mineral rights that are required to permit a well.

power on pecuniary and non-pecuniary leasing outcomes.

The lease quality fits into the matching framework through Eq. (3). While quality is not endogenously determined in the model of spatial competition, 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.

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

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 Eq. (4).[32]

$$\begin{aligned} &\text{Firm Value:} \qquad \frac{\partial v}{\partial share} + \frac{\partial v}{\partial \theta}\frac{\partial \theta}{\partial share} \\ &\text{Landowner Value:} \qquad \frac{\partial u}{\partial \theta}\frac{\partial \theta}{\partial share} \end{aligned} \tag{4}$$

Estimates from the matching and lease quality models approximate the firm and landowner values to market concentration. From the matching model, the marginal value of increased market shares is captured by $\frac{\partial v}{\partial share}$, and the combined marginal values of additional lease quality are captured by $\frac{\partial v}{\partial \theta}$ and $\frac{\partial u}{\partial \theta}$. The lease quality models capture the effects of market structure on lease quality through $\frac{\partial \theta}{\partial share}$, and there are estimated effects of market structure on royalty and landowner concessions.

4 Identification and Estimation

This section describes the estimation strategy used to identify the two-sided model of NTU, one-to-many matching with a match externality. The following sub-sections describe the specific statistical moments used to identify the parameters of the structural model and the sequence of the estimation strategy. The identification strategy for the reduced form model of lease quality is described in the reduced form results section before presenting the estimates of those models.

[32]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.

4.1 Identification

Point-identification of the model stems from the set of statistical moments, exclusion restrictions, and the use of an equilibrium selection mechanism. Two-sided, one-to-many matching models are prone to have multiple, stable equilibrium unless researchers impose an equilibrium selection mechanism or restrict preferences.[33] The equilibrium selection mechanism used to estimate the leasing model assumes that firms extend offers to landowners, which results in a firm-optimal equilibrium. Assuming that firms extend offers is intuitive in this industry where it is the norm for firms to approach landowners with lease offers and not the reverse.

Firm and landowner negotiation values include exclusion restrictions by assuming different observable characteristics affect the firm and landowner preferences to negotiate and sign a lease, which help identify the model. Firms value parcel features that may affect costs like the size of parcels and proximities to infrastructure. Conversely, landowners may value a lease based on firm characteristics and early exposure to drilling. Much of the early well development in Tarrant County occurred in the rural, northwest region and occurred before 2004, pre-dating the majority of leasing and drilling activity described in the analysis. Technological development opened firms to drill all over Tarrant as the technology combined large-scale hydraulic fracturing used to penetrate tight-shale formations with horizontal laterals. Consequently, pre-2004 drilling behavior is not necessarily predictive of the studied drilling behavior and spatial patterns that encompass most of the county from 2004 through 2013. 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' leasing preferences and holding the terms of the lease constant.

Several types of moments are used to estimate the model including those that compare the statistical moments of the observed and simulated matches, moments that use within group variation, and those that use the endogenously determined market structure, $share_j^m$. Each of the moments used to estimate the model are described in greater detail in Table 1. The first set of moments in Table 1 describe the assortative matching behavior across the two sides of the market, and they include the joint distribution and covariance across matched landowner and firm characteristics. Assortativity in the data is demonstrated at

[33] 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.

the beginning of Section 7.

The second set of firm-level moments utilize the econometric result of Agarwal and Diamond (2014) (and applied to the resident-to-hospital match in Agarwal (2015)), which demonstrates that one can use the one-to-many feature of the matching market to identify the parameters when there is not perfect assortativity across match partners. In the lease data, we might find that firms offering more landowner concessions are not necessarily signing leases with larger parcel landowners that are located nearer to the future drill site, which are both attractive features. 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 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.

The third and fourth sets of moments identify the firms' preferences for signing leases across geographic sub-regions of Tarrant County, which requires estimating the effect of the match externality, $share_j^m$, in firms' value functions. The third set of moments utilize the geographic clustering of landowners' parcels by calculating within-market moments that identify parameters describing how firms sort across space. The fourth set of moments utilize the simulated market structure resulting from the deferred acceptance algorithm, which is described in greater detail in the Section 4.2. Table 2 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 market share in firms' values for feasible landowner matches. 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).

4.2 Estimation

This section describes the estimator used to identify the model and the simulation technique for a match with externalities. 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.

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 (5). The moments of the observed data are denoted $\hat{m}$ while the average moments from the set of simulated outcomes are denoted

$\hat{m}(\Omega)$.[34]

$$||\hat{m} - \hat{m}^S(\Omega)||_W^2 = (\hat{m} - \hat{m}^S(\Omega))'W(\hat{m} - \hat{m}(\Omega)) \quad (5)$$

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.[35] The deferred acceptance algorithm[36] facilitates a pairwise stable matching for each draw.[37] 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 assuming that $share_{0,j}^m = share_j^m$ 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_{ij}^s and ξ_{ij}^s, 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 1. The simulated draws are constant across each guess of the

[34]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.

[35]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.

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

[37]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.

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.

4.3 Model and Estimation Assumptions

The model set-up and estimation rely on several assumptions or simplifications, and they are detailed in this sub-section. These assumptions describe 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.

To analyze the distributional consequences of market power, the estimated model assumes utility is non-transferable, whereby non-transferable utility (NTU) jointly maximizes the two sides' separate and exogenous utility functions. NTU allows preferences to be estimated separately for both firms and landowners, while transferable utility maximizes a joint surplus in which utility can be transferred at a constant exchange rate across both sides of the market. Oil and natural gas leases are comprised of royalty rates stipulating how future profits are split across firms and landowners, a fixed bonus paid when the lease is signed, and auxiliary clauses that make up the set of landowner concessions. Expected royalties enter firm and landowner values through the money metric, unobserved bonuses enter through negotiation pair shocks to firm and landowner values, and auxiliary clauses enter values through lease quality measures. Allowing the contract components to enter firm and landowner values directly, I am able to estimate heterogeneous preferences for these and other dimensions of the firm and landowner pairs that are observed signing oil and natural gas leases in the data.

The matching model is estimated as a static, one-shot equilibrium. This implies that the matching model does not account for any dynamics in matching across periods in the data. The matching analysis is used to capture the distributional and heterogeneous implications of market concentration across firms and landowners when there is preference complementarity. Estimating a dynamic matching model requires an additional level of computational complexity beyond the present analysis. However, two important features of the data suggest that a static framework likely captures the desired market interactions of interest. The money metric entering the match value functions and describing 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 results described in Section 7 and reported in Table 7 are impervious to time fixed effects as are the relationships between market structure and lease quality outcomes.[38] These observations suggest that statistical moments based on the static matching outcomes identify important patterns regarding the final market structure and lease quality in the data independent of the timing.

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, drilling, and producing from a well. However, when the leasing firm is not an operator of the well, it is difficult to identify in the data whether a firm transfers the lease to another firm or maintains a royalty interest stake in any future well that is drilled. 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 are publicly reported for all wells in Texas. 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.

5 Data

The estimated model relies on data that describes a series of one-to-many matches between firms and landowners spread across Tarrant County, Texas and spanning the years 2003 to 2013. Those years bound the large influx of natural gas production in the region as a consequence of technological innovation in the industry. There are three primary sources of data used in the analysis: lease data that describes the specific terms of the leasing documents; well permitting and production data occurring between 1990 and 2013 that describes firms' operating activities; and housing data that describes the parcel attributes and physical locations across Tarrant County.

The data set is constructed at the parcel level, which requires matching each leasing document to a parcel by address and buyer/seller/owner names using string matching techniques. To control for potential economies of scale and firm characteristics, the parcels are

[38]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.

mapped to nearby well activity. This is achieved by measuring the distance between leased parcels and nearby well production at the date the lease is signed within a defined buffer of the parcels' geographic location (2000 meter buffer). Below I describe the primary sources of the data and refer readers to the appendix for more detailed data collection and assembly descriptions.

5.1 Lease Data

Leases are publicly (and digitally) available documents filed with the county clerk offices. I observe the identities of the the firms and landowners signing the leases, the date the lease was signed, the acreage of the mineral estate, and coarse geographic descriptors. Each leasing contract is comprised of primary and auxiliary clauses. Primary clauses are found 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, the 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,[39] or fixed payments owed to landowners when the lease is signed. Table 3a 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. The 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 3b summarizes the auxiliary clauses in the data and how specific clauses are sub-categorized into types of landowner concessions, and refer to the appendix for a more thorough discussion of clause types.

Because the bonus sample is comparatively small, analyses explicitly incorporating the bonus payments are reported in the Appendix. However, bonuses are not excluded from the matching analysis, and in the data, there is evidence that a lease containing more landowner concessions likely contains higher royalties and bonus payments, which alleviates concern that landowners trade-off non-pecuniary for pecuniary contracting terms that may not be captured without a more comprehensive bonus sample. In the matching analysis, unobserved bonus payments enter firm and landowner values through the unobserved, negotiation shocks (η_{ij} and ξ_{ij} as described in Section 3) for each potential firm and landowner pair, along with other unobservable (to the econometrician) attributes of individual negotiations. Second,

[39] Only two percent of the bonus payments are observed in the data sample, and 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.

Table 3c describes the raw correlations across the dimensions of lease quality. Without controlling for any other observable characteristics, Table 3c describes a world in which features of the contracts are positively correlated.[40] The positive correlations suggest that a good lease for landowners is good in all dimensions, and landowners are not necessarily compensating fewer clauses with higher royalty rates or bonus payments, for example.

5.2 Well Data

There are publicly available data describing every permitted and producing well in the state of Texas, along with monthly well production values; this data can be accessed through both Drilling Info[41] and the Texas Railroad Commission (TRC)[42]. Each well observation includes important dates like the date the permit was issued by the TRC, and the spud, completion, and first production dates. They also report the operator of the well, the size of acreage permitted, and lateral depths and lengths, among other well characteristics.

Each permit (and well) is geographically identified and is mapped to leasing activity based on proximity to the lease parcels at the date the lease is signed. This allows me to calculate the count of nearby wells for each firm (and their competitors) in the data when they are deciding where to sign leases capturing potential economics of scale in production. Often several wells will be drilled in close proximity, which is classified as a wellpad, and I cluster wells into wellpads by identifying wells drilled within 63 meters of one another.

Other well activity measures are described in Table 4a and used in the matching analysis to describe firm types. These include measures of drilling activity in Tarrant County and in the Barnett Shale, more generally, before 2004 when much of the leasing in Tarrant County began, and the frequency with which firms submit pooling and field rule applications to the Texas Railroad Commission.[43] Table 4a also describes the frequency of landmen and large operators signing leases in the data, and a measure of pre-2004 complaints filed with TRC regarding firm drilling behavior. The violation data is collected from the TRC, which includes inspection dates and the type of violation incurred. The variable in the analysis is the sum of firms' violations. 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.

[40]Longer term lengths are interpreted to be less beneficial for landowners that are restricted from signing lease with other firms or using the minerals other purposes until the primary term expires. A negative correlation between term length and (1) royalty and (2) clause quality is interpreted to contain better/more landowner concessions.

[41]My access to Drilling Info is through the Duke University Energy Initiative.

[42]`http://www.rrc.state.tx.us/`

[43]These variables are used as instruments to break potential endogeneity between market structure and lease outcomes in Section 6.

5.3 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.[44] Further, they supplied appraisal and the available reported sale values[45] for each property type going back to 2008, a data set that also includes house and property characteristics like parcel and house size, the count of room types, and whether the unit is residential, among other descriptive characteristics. The analysis focuses on single-family, residential properties, and Table 4b 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, subsequently, 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 leased mineral estates, which is described Section 5.4.

5.4 Variable Construction

There are several variables constructed from observed leasing activity and used in the empirical analysis, and this section briefly describes how the the variables are calculated and their purpose. I describe how leases (parcels) are assigned to wellpads that extract natural gas from their mineral estate, the measures of firm competition, and measures of future expected income from an active well site.

Each horizontal well has a horizontal lateral extracting from beneath clusters of parcels; 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.

Market concentration is measured by share of leases signed by a firm in a geographic region, cumulative firm shares across time and space.[46] Wellpad clusters are the primary geographic market; however, the empirical results are robust to a more exogenous definition of market delineated by the Tarrant County Appraisal office, abstracts, which are reported in the Appendix.

The future expected royalty payments are a money metric used to monetize the value of non-pecuniary attributes in the matching model. The money metric comprises the expected future natural gas production, using the observed gas production,[47] royalty rate, parcel

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

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

[46] The results are robust to different measures of market structure like the Herfindahl-Hirschman Index, aggregate market share, and firm count, which are reported in the Appendix.

[47] Natural gas production has a steep decline rate in that a bulk of the natural gas is produced within the

size, and total acreage leased for the well. Expected future gas profit for a well sums the product of monthly production, q_{wt}, and the average monthly gas price, p_t^{ng}. The sum of future production is scaled by the parcel size relative to the well acreage, royalties, and an annualizing factor of 0.05 as demonstrated in Eq. (6)

$$\begin{aligned} &\text{Grantee revenue: } \Lambda_{firm} \equiv 0.05(1-r_{ij})\frac{a_i}{\sum_{\forall i' \in w} a_{i'}}\sum_{t=1}^{T} q_{wt}p_t^{ng} \\ &\text{Grantor revenue: } \Lambda_{parcel} \equiv 0.05 r_{ij}\frac{a_i}{\sum_{\forall i' \in w} a_{i'}}\sum_{t=1}^{T} (q_{wt}p_t^{ng}) \end{aligned} \tag{6}$$

The current revenue values do not account for costs accrued to producers from drilling the well or any forgone opportunity costs of investing after the minerals are leased but before the well is drilled. The last row of Table 4b summarizes the annualized revenues for parcels across Tarrant County.

6 Results: Instrumental Variable Models

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,[48] 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.[49]

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.

[48]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.

[49]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

6.1 Identification

Instrumental variables are used to mitigate omitted variable bias, breaking potential endogeneity between market structure and lease outcomes. 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. Conversely, markets may have more active property rights attorneys or groups of landowners may jointly negotiate leases through community organizations, which may drive up the landowner concessions written into leases signed in that market. However, the same regional characteristics may deter some 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 the potential omitted variables.

I propose two instrumental variables to break potential endogeneity between market structure and lease outcomes like royalty, term length, and landowner concession clauses. The first measures firms' pre-2004 drilling activity in nearby markets and their regulatory prowess as measured by the count of firms' approved applications to pool or be granted new field rules with the Texas Railroad Commission. Drilling in Tarrant County before 2004 was isolated to the rural, northwest corner of the county. Technological innovation that combined large-scale hydraulic fracturing able to penetrate tight-shale formation with horizontal laterals freed firms to lease and drill in densely populated regions, characterizing the a large part of Tarrant County. The instrument is invalid if pre-2004 drilling behavior in nearby markets is correlated with current contracting behavior, driving the types of terms written into the leasing agreements. However, these leases are signed at least one or two kilometers away from pre-2004 drilling activity and, on average, at least three years after. Further, firms that are more active in earlier periods, like Mitchell and Devon, are not necessarily the most active in later periods suggesting that a firm's pre-2004 drilling activity should not be correlated with a firm's expected productivity, a factor which may be positively correlated with leases containing more landowner concessions.

The second instrument uses 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 in Tarrant County. I propose instrumenting market structure with regulatory experience (and success) using variables that describe firms' approved applications to the TRC for pooled drilling units and units with unique field rules. The instrument is

and landowners. `https://stateimpact.npr.org/pennsylvania/tag/royalties/`

invalid if the past frequency of TRC approved applications across all of Texas is correlated with the specific contracting terms written into privately negotiated leases transferring Tarrant County parcels. However, leases are largely negotiated on dimensions not related to pooling or field rules. Though there are specific lease terms that address pooling limitations specifically, these clauses are not included in the analysis because they follow a uniform industry standard.[50]

6.2 Results

Tables 5 and 6 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 controls that describe the parcel characteristics like the size of the parcel, whether it is located in a rural area of Tarrant, 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. Eq. (7) describes the estimating equation in which θ_{ij} takes on values for the different measures of landowner concessions and $share_j^m$ is firm j's market share in market m in which landowner i is located.

$$\theta_{ij} = \delta X_i + \gamma share_j^m + \epsilon_{ij} \tag{7}$$

Table 5 reports the OLS and 2SLS results for lease quality measures that have pecuniary value, which includes *Royalty Rates*, *Term Length*, and *Post Production Costs*. The estimates for the primary variable of interest, *Lease Share*, are reported in the first row. Comparing the first three OLS columns to the last three 2SLS columns, the instrument takes significance from royalty and increases the magnitudes of the significant effects on *Term Length* and *Post Production Cost*. Focusing on the 2SLS estimates, I find that a greater market share has a negative effect on *Royalty* (-0.010) and the inclusion of a *Post Production Cost* clause (-0.569**) and a positive effect on *Term Length* (40.397***). 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

[50] 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.

deductions taken out of owed royalties. A firm with a fifty percent market share is almost thirty percent less likely to sign a lease with a *Post Production Cost* clause (-0.569*0.5).[51] Finally, *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 royalties, 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.

Table 6 reports the results for non-pecuniary lease quality measures, or auxiliary clauses that have been grouped by clause types as described by Table 3b. 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 almost forty percent fewer clauses, which is roughly two 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 of the *Full*, *Dis-amenity*, and *Water* clauses are amplified with use of the instruments. The effect on *Surface* is no longer significant, and the sign flips to a more intuitive effect of market power on *"Bads."*

Specifications reported in the appendix demonstrate robustness to a different definition of geographic market, selections of instrumental variables,[52] definitions of market structure,[53] 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 and inclusion of lease year fixed effects. Further, the Appendix includes fixed effects regressions that estimate the effects of market share on lease outcomes along with fixed effects 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.

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

[52] Additional instruments include distances between leased parcel and the Tarrant County Clerk (TCC) office and between firms' local offices and the TCC.

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

7 Results: Matching Model

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 7 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 7a and landowners' assortativity in Table 7b. 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 7a. 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 3.5 describing the lease quality model. Additionally, lease quality and expected profitability have a strong positive relationship (2.094***). In Table 7b, 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 7a, lease quality is negatively related to market structure (-0.137***).

Table 8 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 8 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 8 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 9 split between the parameters characterizing firm values as reported in Table 9a and those characterizing landowner values in Table 9b. The model captures heterogeneity in firm preferences for parcel attributes as defined by the second column of Table 9a. Each parameter value is monetized by the annualized value of the future expected profit derived from signing a particular lease, or the money metric as described in Section 5, which is normalized to one when estimating the matching model. In general, the estimates of the matching model fit the hypotheses proposed in Section 3. Firms view more landowner concessions as costly while landowners value the added protection, and firms value spatial complementarity.

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 9a. Using the *Dis-amenity Bundle* summary statistics in Table 3b, 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 9a 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 9b, 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 dis-amenities.

7.3 Model Fit

Table 10 describes how well the estimated match equilibrium from Table 9 captures the observed market structure in the data. Table 10a 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 10b 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.[54] 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 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 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.

Under uniform leasing, firm j ranks their preferences for landowners based on the values for each parcel, $f(X_i, Z_j, \theta; \beta) + \beta share_j^m + \eta_{ij}$, where θ is now fixed for all firms and landowners.[55] 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 cause them to signer fewer leases altogether. Further, the cost to sign specific lease terms is homogeneous for all firm and landowner pairs, which causes firms to value parcels' observable characteristics and market share more.

In addition to uniform leasing, I test how the market responds to requiring an environmental clause and a single clause with external benefits to all leases signed. Requiring an environmental clause increases the cost to lease for a subset of firms, while requiring a single clause increases the costs to all firms. The final policy experiment allows lease quality to depend negatively on market structure, which combines the matching and lease quality

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

[55]Landowner preferences are represented by ranking firms' offers based on $g(X_i, Z_j, \theta; \alpha) + \xi_{ij}$.

modeling frameworks.

8.1 Results

Table 11 reports the changes to market structure (HHI) and to the total count of leases signed by firms.[56] 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 11 reports that there is no measurable change to the market structure when royalty is fixed at a higher rate.

The fourth row of Table 11, *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.[57] The fifth row of Table 11, *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.

The sixth row of Table 11 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 costly option to uniform leasing may be requiring a set of particularly valuable clauses for landowners.[58]

The final set of counterfactuals allow the quality of leases signed to adjust with the market structure according to the relationships estimated in simple OLS models of lease quality. The two equations in Eq. (8) represent lease quality and firm and landowner values, respectively. Embedding parameter estimates from the reduced form models (reported in the first column

[56] For each counterfactual, preferences are ranked, firms are matched to landowners via the Deferred Acceptance Algorithm, 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 $share^{m,t} - share^{m,t-1} = 0$.

[57] 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.

[58] 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.

of Table 11) into the matching framework, the models converge to new equilibria.

$$\begin{aligned} \hat{\theta}_{ij} &= \hat{\alpha}_0 + \hat{\alpha}_1 share_j^m + \hat{\alpha}_2 X_j \\ v_{ij} &= f(X_{i'}, Z_j, \hat{\theta}_{i'j}; \hat{\beta}) + \hat{\beta} share_j^m \\ u_{ij} &= g(X_{i'}, Z_j, \hat{\theta}_{i'j}; \hat{\beta}) \end{aligned} \tag{8}$$

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 unit, Eq. (9), and the value of the change to lease quality.[59]

$$\begin{aligned} &\Delta_{i,in}^{base,cf} \equiv E[u_{ij}(\Lambda_{parcel}^{in}, X_i, Z_j, \theta_{ij}^{cf}; \hat{\alpha})] - u_{ij}(\Lambda_{parcel}^{base}, X_i, Z_j, \theta_{ij}^{base}; \hat{\alpha}) \\ &\text{where } \Lambda_{parcel}^{in} = 0.05 r_{ij} \frac{a_i}{\sum_{\forall i' \in w^{cf}} a_{i'}} \sum_{t=0}^{T} q_{w,t} p_t^{ng} \end{aligned} \tag{9}$$

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. (10), and the expected lost lease quality from the clauses with private benefits, $\theta_{ij}^{cf,private}$.[60]

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

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

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

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}.

$$\Delta_j^{base,cf} \equiv \Lambda_{firm} + E[v'_{ij}(X_i, Z_j, share_j^{cf}, \theta_{ij}^{cf}; \hat{\beta})] - v'_{ij}(X_i, Z_j, share_j^{base}, \theta_{ij}^{base}; \hat{\beta}) \tag{11}$$

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 12, 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 12 describes the total welfare change for landowners. The most beneficial policy is a single added clause (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

Using private contracting terms, this paper estimates the effects of market power on the pecuniary and non-pecuniary outcomes of contracts that transfer mineral rights to firms for oil and natural gas drilling. 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 transferring spatially clustered mineral rights. As a result, I extend the specific matching framework to allow identification of a model with a specific type of complementary preferences by introducing a set of statistical moments. Through this extension, I am able to estimate the value of economies of density in this market. Further, 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 dis-amenities by requiring stricter leasing standards is a low cost mechanism to limit their exposure to drilling risks.

References

Agarwal, N. (2015): "An empirical model of the medical match," *The American Economic Review*, 105(7), 1939–1978.

Agarwal, N., and W. Diamond (2014): "Identification and estimation in two-sided matching markets," .

Ashlagi, I., M. Braverman, and A. Hassidim (2014): "Stability in large matching markets with complementarities," *Operations Research*, 62(4), 713–732.

Azevedo, E. M., and J. W. Hatfield (2012): "Complementarity and multidimensional heterogeneity in matching markets," *Unpublished mimeo.*

Baccara, M., A. İmrohoroğlu, A. J. Wilson, and L. Yariv (2012): "A field study on matching with network externalities," *The American Economic Review*, pp. 1773–1804.

Bando, K. (2012): "Many-to-one matching markets with externalities among firms," *Journal of Mathematical Economics*, 48(1), 14–20.

Berry, S., and A. Pakes (2007): "The pure characteristics demand model," *International Economic Review*, 48(4), 1193–1225.

Biró, P., and F. Klijn (2013): "Matching with couples: a multidisciplinary survey," *International Game Theory Review*, 15(02), 1340008.

Boxall, P. C., W. H. Chan, and M. L. McMillan (2005): "The impact of oil and natural gas facilities on rural residential property values: a spatial hedonic analysis," *Resource and energy economics*, 27(3), 248–269.

Boyd, D., H. Lankford, S. Loeb, and J. Wyckoff (2013): "Analyzing the determinants of the matching of public school teachers to jobs: Disentangling the preferences of teachers and employers," *Journal of Labor Economics*, 31(1), 83–117.

Che, Y.-K., J. Kim, and F. Kojima (2014): "Stable matching in large economies," Discussion paper, mimeo.

Code, N. R. (2015a): "Natural Resources Code," .

Code, T. A. (2015b): "Texas Administrative Code, Title 16, Part 1, Chapter 3.," .

Ellickson, P. B., S. Houghton, and C. Timmins (2013): "Estimating network economies in retail chains: a revealed preference approach," *The RAND Journal of Economics*, 44(2), 169–193.

Fitzgerald, T. (2010): "Evaluating Split Estates in Oil and Gas Leasing," *Land Economics*, 86(2), 294–312.

Fitzgerald, T., and R. R. Rucker (2014): "US private oil and natural gas royalties: estimates and policy considerations," .

Fox, J. T., and P. Bajari (2013): "Measuring the efficiency of an FCC spectrum auction," *American Economic Journal: Microeconomics*, 5(1), 100–146.

Gale, D., and L. Shapley (1962): "College Admissions and the Stability of Marriage," *The American Mathematical Monthly*, 69(1), 9–15.

Gopalakrishnan, S., and H. A. Klaiber (2014): "Is the shale energy boom a bust for nearby residents? Evidence from housing values in Pennsylvania," *American Journal of Agricultural Economics*, 96(1), 43–66.

Gourieroux, C., and A. Monfort (1997): *Simulation-based econometric methods*. Oxford University Press.

Hafalir, I. E. (2008): "Stability of marriage with externalities," *International Journal of Game Theory*, 37(3), 353–369.

Hatfield, J., and P. Milgrom (2005): "Matching with Contracts," *American Economic Review*, 95(4), 913–935.

Hendricks, K., J. Pinkse, and R. Porter (2003): "Empirical Implications of Equilibrium Bidding in First-Price, Symmetric, Common Value Auctions," *Review of Economic Studies*, 70(1), 115–145.

Hill, E. L. (2013): "Shale gas development and infant health: evidence from Pennsylvania," *Charles H. Dyson School of Applied Economics and Management, Cornell University, Working Paper. Available at.*

Hill, E. L., and L. Ma (2017): "Shale Gas Development and Drinking Water Quality," *forthcoming in American Economic Review Papers and Proceedings.*

Holmes, T., B. Seo, and M. Shapiro (2015): "Competition for land and economic density," *Working Paper.*

Holmes, T. J. (2011): "The Diffusion of Wal-Mart and Economies of Density," *Econometrica*, 79(1), 253–302.

James, A., and J. James (2014): "A Canary Near a Gas Well: Gas Booms and Housing Market Busts in Colorado," *Work. Pap.*

Jia, P. (2008): "What happens when Wal-Mart comes to town: An empirical analysis of the discount retailing industry," *Econometrica*, pp. 1263–1316.

King, J. C. (2011): "Selected re-emerging and emerging trends in oil and gas law as a result of production from shale formations," *Texas Wesleyan Law Review*, 18, 1–18.

Kojima, F., P. A. Pathak, and A. E. Roth (2013): "Matching with couples: Stability and incentives in large markets," Discussion paper.

Konschnik, K., and M. Boling (2014): "Shale gas development: a smart regulation framework," *Environmental science & technology*, 48(15), 8404–8416.

LEWIS, E. (2015): "Federal Environmental Protection and the Distorted Search for Oil and Gas," *Working Paper*.

LIBECAP, G. D., AND S. N. WIGGINS (1985): "The influence of private contractual failure on regulation: the case of oil field unitization," *The Journal of Political Economy*, pp. 690–714.

MCFADDEN, D. (1989): "A method of simulated moments for estimation of discrete response models without numerical integration," *Econometrica: Journal of the Econometric Society*, pp. 995–1026.

MUEHLENBACHS, L., E. SPILLER, AND C. TIMMINS (2015): "The Housing Market Impacts of Shale Gas Development," *forthcoming in the American Economic Review*.

NISHIDA, M. (2014): "Estimating a model of strategic network choice: The convenience-store industry in Okinawa," *Marketing Science*, 34(1), 20–38.

OLMSTEAD, S., AND N. RICHARDSON (2014): "Managing the Risks of Shale Gas Development Using Innovative Legal and Regulatory Approaches," *Wm. & Mary Envtl. L. & Pol'y Rev.*, 39, 177.

PAKES, A., AND D. POLLARD (1989): "Simulation and the asymptotics of optimization estimators," *Econometrica: Journal of the Econometric Society*, pp. 1027–1057.

PORTER, R. H. (1995): "The Role of Information in U.S. Offshore Oil and Gas Lease Auctions," *Econometrica*, 63(1), 1–27.

PYCIA, M., AND B. YENMEZ (2015): "Matching with Externalities," *University of California Los Angeles Working Paper*.

RICHARDSON, N., M. GOTTLIEB, A. KRUPNICK, AND H. WISEMAN (2013): *The state of state shale gas regulation*. Resources for the Future Washington, DC.

SASAKI, H., AND M. TODA (1996): "Two-sided matching problems with externalities," *Journal of Economic Theory*, 70(1), 93–108.

TIMMINS, C., AND A. VISSING (2015): "Environmental Justice and Coasian Bargaining: The Role of Race and Income in Lease Negotiations for Shale Gas," *Working Paper*.

TRAIN, K. (2000): "Halton sequences for mixed logit," *Department of Economics, UCB*.

TRAIN, K. E. (2009): *Discrete choice methods with simulation*. Cambridge university press.

UETAKE, K., AND Y. WATANABE (2013): "Entry by Merger: Estimates from a Two-Sided Matching Model with Externalities," *Working Paper*.

URBINA, I. (2011): "Drilling down series," *The New York Times*.

Vengosh, A., R. B. Jackson, N. Warner, T. H. Darrah, and A. Kondash (2014): "A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States," *Environmental science & technology*, 48(15), 8334–8348.

Zeik, T. (2009): "Hydraulic fracturing goes to court: How Texas jurisprudence on subsurface trespass will influence West Virginia oil and gas law," *West Virginia Law Review*, 112, 599–636.

Table 1: 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 2: 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 2 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 3: 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.
Dis-amenity Bundle	0.106	(0.198)	Legal Bundle	0.165	(0.213)
Environmental	0.177	(0.382)	Force Majuere	0.330	(0.47)
Noise	0.220	(0.414)	Pugh	0.115	(0.318)
Freshwater Protect	0.016	(0.124)	Offset Well	0.261	(0.439)
Surface Casing	0.005	(0.068)	Insurance/Indemnity	0.040	(0.197)
Compression Station	0.007	(0.086)	Record Keeping	0.078	(0.268)
Surface Bundle	0.328	(0.274)	"Bads" Bundle	0.336	(0.389)
No Surface Access	0.543	(0.498)	Subsurface Easement	0.463	(0.499)
Surface Use Rest.	0.031	(0.174)	No Litigation	0.210	(0.407)
Damage	0.410	(0.492)			
Water Protection Bundle	0.066	(0.148)	Post-Production Cost	0.182	(0.386)
Freshwater Protection	0.016	(0.124)			
Surface Casing	0.005	(0.068)			
Environmental	0.177	(0.382)			
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 4: 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 5: Lease Quality Estimates - Primary Terms

	(1) Royalty	(2) Term (month)	(3) Post Prod. Cost	(4) Royalty	(5) Term (month)	(6) Post Prod. Cost
		OLS			*2SLS*	
Lease Share (Firm)	-0.012***	8.115***	-0.068**	-0.010	40.397***	-0.569**
	(0.002)	(1.225)	(0.034)	(0.008)	(9.560)	(0.260)
Land size (100 sqft)	0.000**	-0.056***	-0.001*	0.000***	-0.022	-0.001**
	(0.000)	(0.009)	(0.000)	(0.000)	(0.018)	(0.000)
Dist to WP (Inv)	-0.000	-0.002**	0.000	0.000	-0.003**	0.000
	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Rural	-0.002	-10.328***	0.113***	-0.002	-8.943***	0.073
	(0.002)	(0.846)	(0.041)	(0.003)	(1.879)	(0.047)
Rural*Land size	-0.000***	0.029**	0.001	-0.000***	-0.041	0.001*
	(0.000)	(0.013)	(0.001)	(0.000)	(0.032)	(0.001)
18-Mon. Oil Future	0.000***	-0.077***	0.004***	0.000***	0.120*	0.001
	(0.000)	(0.018)	(0.001)	(0.000)	(0.064)	(0.002)
18-Mon. NG Future	-0.002***	0.020	0.025***	-0.002***	-1.263***	0.049***
	(0.000)	(0.168)	(0.003)	(0.000)	(0.449)	(0.011)
Pred. Oil Volatility	0.024***	-8.953***	0.593***	0.030***	-10.648***	0.668***
	(0.003)	(1.972)	(0.081)	(0.003)	(3.103)	(0.099)
Pred. Gas Volatility	-0.061***	9.105	-0.138	-0.084***	1.867	-0.069
	(0.012)	(6.434)	(0.136)	(0.010)	(7.681)	(0.152)
Constant	0.239***	51.938***	-0.935***	0.250***	37.467***	-0.725***
	(0.008)	(4.456)	(0.123)	(0.008)	(7.470)	(0.225)
Observations	151,734	152,234	150,501	151,734	152,234	150,501
R-squared	0.324	0.130	0.213	na	na	na
Clustered Std. Err.	Yes	Yes	Yes	Yes	Yes	Yes
					First Stage	
Pre-2004, near prod.				-0.157***	-0.518***	-0.157***
				(0.027)	(0.047)	(0.027)
Pooling Approved				-0.011***	-0.010***	-0.011***
				(0.000)	(0.000)	(0.000)
Field Rule Approved				0.084***	0.083***	0.084***
				(0.009)	(0.009)	(0.009)
R-squared				0.165	0.165	0.165
1st stage F-stat				2143	2158	2006

Notes: (i) Each column represents a separate OLS or 2SLS specification regressing lease quality on observable parcel attributes; (ii) 2SLS instruments Firm Cumulative Share with a measure of a firm's nearby well count as of 2004 and the count of pooling and field rule changes filed with the TRC pre-leasing across Texas; (iii) standard errors are clustered by geographic market; (iv) first stage results report only the instrumental variable estimates though each first stage model is estimated using the full set of control variables.

Table 6: Lease Quality Estimates - Auxiliary Terms

	(1) Full Set	(2) Legal	(3) Surface	(4) "Bads"	(5) Dis-amenity	(6) Water
			(a) OLS			
Lease Share (Firm)	-0.082***	-0.021	-0.118***	-0.041**	-0.101***	-0.070***
	(0.022)	(0.019)	(0.018)	(0.017)	(0.017)	(0.012)
Land size (100 sqft)	-0.000	-0.000	-0.000	-0.000	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Dist to well lateral	0.000	-0.000	-0.000*	-0.000***	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Rural	-0.077***	-0.060***	-0.132***	-0.077***	-0.056***	-0.027*
	(0.020)	(0.016)	(0.021)	(0.022)	(0.015)	(0.014)
Rural*Land size	0.001*	0.001**	0.000	0.000	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.218***	0.179***	0.392***	0.247***	0.156***	0.100***
	(0.017)	(0.014)	(0.012)	(0.011)	(0.013)	(0.009)
R-squared	0.014	0.002	0.025	0.005	0.029	0.025
			(b) 2SLS			
Lease Share (Firm)	-0.560***	0.003	-0.076	0.589***	-0.765***	-0.323***
	(0.176)	(0.114)	(0.087)	(0.149)	(0.193)	(0.110)
Land size (100 sqft)	-0.001**	-0.000	-0.000*	0.001**	-0.001**	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Dist to well lateral	0.000	-0.000	-0.000**	-0.000***	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Rural	-0.072***	-0.045***	-0.136***	-0.075**	-0.060**	-0.033**
	(0.027)	(0.015)	(0.019)	(0.034)	(0.030)	(0.016)
Rural*Land size	0.002***	0.000	0.000	-0.001***	0.002***	0.001**
	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)
Constant	0.454***	0.149**	0.367***	-0.084	0.496***	0.229***
	(0.091)	(0.058)	(0.045)	(0.074)	(0.099)	(0.058)
Observations	150,501					
Clustered Std. Err.	Yes					
First Stage						
Pre-2004, near prod.	-0.136***					
	(0.029)					
Pooling Approved	-0.016***					
	(0.000)					
Field Rule Approved	0.198***					
	(0.010)					
R-squared	0.050					
1st stage F-stat	843					

Notes: (i) Each column represents a separate OLS or 2SLS specification regressing lease quality on observable parcel attributes; (ii) 2SLS instruments Firm Cumulative Share with a measure of a firm's nearby well count as of 2004 and the count of pooling and field rule changes filed with the TRC pre-leasing across Texas; (iii) standard errors are clustered by geographic market; (iv) 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: 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 8: 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 9: 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 10: 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 9, 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 11: 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 11 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 12: 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 12 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 ($\Delta_{i,in}^{base,cf} - \Delta_{i,out}^{base,cf}$).