Innovation Below North Dakota*

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Abstract

Using unique microdata, we examine the adoption of hydraulic fracturing (*fracking*) by energy companies drilling for oil in North Dakota. We find that private firms are the very first to implement this disruptive new technology in the early 2000's, and that they also pioneer fracking in new geographic areas in subsequent years. While public firms follow private firms into new areas, we find that public firms more rapidly implement technologies relating to expanding scale and lowering costs. We consider several explanations for these differences in innovative investments, and we present evidence that access to capital plays a significant role.

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1. Introduction

Innovation is a critical factor in economic growth, yet the ways in which a firm's organization affects innovation remain relatively poorly understood. Different theories of financial, agency, and contracting frictions yield different predictions about which types of firms, privately held or publicly traded, should be most innovative. This tension suggests a promising area for empirical analysis. However, innovation is hard to define ex-ante and to quantify ex-post. Most of the related empirical literature examines broadly-defined innovation proxies, such as patents and R&D expenditures, which do not allow for examination of subtitles such as the extent to which public or private firms innovate in different ways.

In this paper, we use unique data which allow us to separately consider investments in two different stages of product innovation, following Schumpeter (1934), by both publicly traded and private held energy firms. Specifically, we examine hydraulic fracturing (*fracking*) (a new invention akin to Karl Benz's first automobile), which we define as *frontier innovation*. In addition, we examine pad drilling (a technological advancement relating to scale as in Henry Ford's automobile assembly line), which we define as *scale innovation*. We find that private firms more aggressively pursue frontier innovation, while public firms pursue scale innovation. We also present evidence suggesting that financing constraints play a significant role in how firms allocate investments across these two aspects of innovation.

Our analysis centers on the dramatic increase in oil production from wells that were drilled and fracked in North Dakota starting in the 2000's. We choose this setting for several reasons. First, the development and widespread adoption of fracking in the oil & gas industry represents one of the most economically significant technological developments in recent history, as we describe below. Second, the North Dakota oil "boom" is driven both by experimentation with different fracking techniques in different geographies (i.e. frontier innovation) and by the advent of factory-like economies of scale in well completion and the delivery of oil to the market (i.e. scale innovation). Third, oil & gas drilling is highly capital-intensive and requires significant reliance on external financing - suggesting access to capital may play a first-order role in determining project choice.[1]

We implement our reserach design using unique data that provides highly specific project level detail on the locations, inputs (including the use of fracking), and outputs of every oil well in North Dakota. These data allow us to characterize the innovative nature of firms' investments with greater precision relative to widely used measures such as R&D expenditures and patents. This last feature is especially important to our setting since most of the development of fracking technology was done without the use of patents (Golden and Wiseman (2014)). It bears noting that since we lack exogenous variation in listing status, all of the evidence we present below is suggestive. However, given that we are providing an important and novel take on a still open empirical question, we believe that our work represents a significant step towards better understanding how much and in what manner private and public firms contribute to the innovation process.

First, we compare the extent to which private and public firms adopt fracking in new areas (frontier innovation). Fracking previously unexplored areas entails significant costs (the average well cost in 2014 was $7.1 million) and risks (30% of newly explored areas are subsequently abandoned). Furthermore, petroleum engineers recognize that even within the Bakken formation, there exists a large degree of geographic variation in both oil recovery rates and sensitivity to fracking inputs (Baihly et al. (2012); Jabbari, Zeng et al. (2012);

[1] In a related paper, Gilje and Taillard (2017) shows that access to capital affects the intensity with which natural gas companies react to changing investment opportunities. We complement their results by providing evidence on how firm finances affect the type of investment made.

Saputelli et al. (2014)) and so trailblazers generate significant information spillovers.

The first frack to occur in our data was executed by a small private North Dakota based company called Nance Petroleum during the winter of 2000. Over the first seven years of our sample (2000-2006) energy companies performed 110 fracks in North Dakota. Of these, private firms performed 62 (56%) and public firms performed the other 48. Aside from being early adopters, private firms also systematically frack new areas with greater frequency. To highlight this result, we define $Frontier\,Share$ as the share of total wells in a quarter that a firm drills in new geographies. Our primary measure of geography is oil fields as defined by the North Dakota Industrial Commission (NDIC). Using this measure, private firms' frontier shares are between 3.6-5.1% larger than those of public firms. This difference is economically significant given that the average public firm frontier share is 7.6%. Our results control for: 1) the fact that private companies in our sample frack fewer wells on average relative to public companies, and 2) the fact that private companies frack a greater share of wells in the early years of the sample when more of North Dakota was open to explore. We also show that private firms' frontier investment create new viable fields - suggesting it truly is innovative.

While private firms engage in more frontier innovation, public firms overweight scale innovation. Our primary measure of scale innovation is the use of multi-well pad drilling - i.e. drilling multiple tightly spaced wells on a single site. Pad drilling saves time and money by cutting down rig disassembly and relocation and by reducing overhead costs of managing multiple drill sites. We find that after controlling for a well's geography and other salient characteristics (e.g. depth), pad drilling reduces drilling times by about 7%, yielding around \$30,000 in saving per well. Analogous to frontier share, we define $Pad\,Share$ as the fraction of wells a firm drills in a quarter that belong to a multi-well pad. We find that public firms pad shares are on average about 30% larger than private firm pad shares - a statistically and economically significant difference.

Finally, we provide evidence consistent with differential access to capital markets playing a role in patterns we observe. We construct firm level proxies for North Dakota oil reserves and find that in response to a $10 million change in reserves, private firms reduce their frontier share by 14 basis points, which represents an 1.1% reduction relative to the average private firm's frontier share. That same gain in reserves yields a 52 basis point increase in pad drilling share - a 2% increase over the average pad drilling share of private firms. Importantly, the sensitivity of innovation choice to reserves is stronger for private than for public firms, which is consistent with the notion that private firms rely on their reserves as collateral for credit to a much higher degree. Also, since our estimates hold *within firm* (i.e. with firm fixed effects), we can rule out that differences between private and public firms are driven by time-invariant characteristics that affect both innovation and listing choice.[2]

This paper contributes most directly to the literature regarding innovation decisions of public versus private firms. Theoretical arguments generate ambiguous predictions regarding listing status and innovation. If public markets reduce information asymmetry, say via price informativeness (Grossman and Stiglitz (1980)), then public equity markets can reduce cost of capital and foster firm innovation (Rajan (2012)). On the other hand, the separation of ownership and control in public companies generates agency conflicts (Jensen and Meckling (1976)), which may lead to either over- or under-investment in innovative projects. Additionally, shareholder myopia may force a focus on near-term profits at the expense of long-run value (Stein (1989); Bolton, Scheinkman, and Xiong (2006)).

[2]For example, one may be concerned that managerial expertise or risk appetite leads certain firms to specialize in frontier innovation and others to specialize in scale innovation and that frontier innovators choose to remain private due to the fixed cost of IPOs (Ritter (1987)) or due to disclosure reasons (Farre-Mensa (2017)).

Given the theoretical ambiguity regarding listing status and firm innovation, it is not surprising that the empirical findings on the matter are mixed as well. Acharya and Xu (2017) find that limited access to finance leads private firms to innovate less in industries that are external finance dependent. Bernstein (2015) shows that after going public firms shift from the internal generation to the acquisition of innovation. He and Tian (2015) find that price informativeness and monitoring of short sellers enhance innovation. In contrast, He and Tian (2013) find that analyst coverage can exacerbate managerial myopia and Fang, Tian, and Tice (2014) find that increased liquidity makes the firm more vulnerable to takeovers and more attractive to short-term investors, all of which reduce innovation incentives. We contribute to this literature by demonstrating that reduced access to capital markets shifts the nature of innovative activity.

This paper is also related to a literature in economics that uses the oil E&P industry as a laboratory for studying how productivity evolves. The extant papers in this literature focus on learning, either from experience or via informational spillovers (Corts and Singh (2004), Kellogg (2011), Covert (2015), Levitt (2016)), and do not condition on listing status. This paper extends this literature by documenting that private and public firms propagate different kinds of technologies.

The remainder of the paper is as follows. Section 2 provides an overview of Fracking and its economic and geopolitical significance. Section 3 describes our data. Section 4 details our empirical results. Section 5 concludes.

2. Fracking Overview

The widespread adoption of hydraulic fracturing (*fracking*) in the oil & gas industry is among the most economically significant technological innovations in recent decades. Healy (2012) succinctly defines fracking:

> Hydraulic fracturing, or 'fracking', is a method used by drilling engineers to stimulate or improve fluid flow from rocks in the subsurface. In brief, the technique involves pumping a water-rich fluid into a borehole until the fluid pressure at depth causes the rock to fracture. The pumped fluid contains small particles known as proppant (often quartz-rich sand) which serve to prop open the fractures.

Engineers performed the first frack in Kansas in 1949, as discussed in Montgomery, Smith et al. (2010). Energy firms initially used fracking to stimulate the production of natural gas, and eventually adapted fracking to crude oil production.

As we show in Appendix Figure A1, energy firms in North Dakota first began adapting fracking to oil drilling in the early/mid-2000's. Fracking involves added costs, as fleets of trucks pump over 150,000 barrels of frack fluids into wells at pressures exceeding 9,000 pounds per square inch (psi). In addition, fracked wells must be deep enough to reach shale-rock formations which are generally at least two miles below ground, and then extend horizontally within the cross-section of the shale for another one or two miles. These factors can double or triple the cost of a fracked well relative to that of a non-fracked well. However, as we show in Appendix Figure A2, fracked wells produce oil at far higher rates than non-fracked wells on average.

The gains in oil production, relative to the added costs, resulted in a boom in oil fracking investment, primarily in shale formations below North Dakota and Texas starting after 2009. According to the U.S. Energy Information Agency (EIA), drilling fracking and leasing costs in North Dakota average between $7-10 million per well.[3] Our sample consists of 11,313 wells,

[3] See the EIA's "Trends in U.S. Oil and Natural Gas Upstream Costs": https://tinyurl.com/zh4kdvx.

which implies an aggregate capital investment of more than $80 billion, the bulk of which occurs between 2010 and 2015. This does not capture investments in pipelines, processing plants, terminals, and other infrastructure necessary for getting the oil from North Dakota to refineries in the U.S. Mid-Continent and Gulf Coast regions. EIA data indicates that shale drilling in Texas is roughly three-fold higher than in North Dakota, which suggests that the overall shale boom rivaled (or possibly exceeded) the telecom boom of the late 1990's in terms of aggregate dollars invested, according to the capex figures in Doms (2004).

The drilling and fracking boom in North Dakota over the past decade, compounded by increases in oil production per well, contributed to dramatic increases in crude oil production in North Dakota and in the U.S., which we show in Appendix Figure A3. Between 2000-2016, the years spanned by our sample, North Dakota's aggregate oil production grew more than 10-fold: from less than 100,000 barrels per day to over 1 million barrels per day. During this time North Dakota went from accounting for from less than 1% of total U.S. crude oil production to over 12%. Currently, North Dakota is the second largest oil producing state (behind Texas). According to the EIA, oil flowing from fracked wells accounts for over half of aggregate U.S. production as of 2016, and accounted for the entirety of the crude oil production growth over the past decade.[4]

The recent growth in U.S. crude oil production has disrupted import/export dynamics and lowered global energy prices. Between 2008-2016 total U.S. crude oil imports fell 20%, and U.S. imports from OPEC countries fell 40%. These declines are remarkable considering that U.S. GDP expanded by 24% over the same period (according to the World Bank). Crude oil prices in recent years are dramatically lower than in the years prior to the 2010-2015 fracking boom. Outside of the U.S. many sources of energy, such as liquefied natural gas (LNG), are

[4] See the EIA's "Today In Energy" on March 15th, 2016: https://tinyurl.com/y9fdb4no.

indexed to crude oil prices. Therefore, fracking in the U.S. has contributed to lower energy prices throughout the world. These developments have significant implications for the global economy and global geopolitics, as discussed in Blackwill and O'Sullivan (2014).

3. Data

We define variables using data from 11,313 oil wells in North Dakota as proxies for both frontier and scale innovation. We also define variables at the firm level to that proxy for financing constraints and other characteristics. We summarize variables for the largest firms in our sample in Appendix Table A1 and summarize all variables, at both the well i level, and aggregated at firm j level, in Table 1.

3.1. North Dakota Oil Well Data

We assemble data for 11,313 unique oil wells from the NDIC for our analysis.[5] Each of the wells in our sample is an oil well, which is drilled into the Bakken shale formation, and is completed using hydraulic fracturing (fracking).[6]

We measure productivity using $Oil\ Production_{i,j}$ which is the number of barrels of crude oil from well i over the first 24-hours that the well produces.[7] We measure salient well characteristics such as $Total\ Depth_{i,j}$ which is the well's total depth (in miles).[8] We measure costs by defining $Drill\ Days_{j,t}$ as the number of days that the drilling rig is on site to drill the well. Rigs are leased by the day, and represent the largest single significant component of a well's total capital cost. As we show in Table 1: our average fracked well is 3.75 miles

[5]Our dataset is similar to the data used in Covert (2015).

[6]We use "wells drilled" and "wells fracked" interchangeably throughout the paper.

[7]Fracking increases a well's initial production, as discussed in the EIA's "Initial production rates in tight oil formations continue to rise": `https://tinyurl.com/yatk5ed8`.

[8]the EIA's "Trends in U.S. Oil and Natural Gas Upstream Costs": `https://tinyurl.com/zh4kdvx` indicates that drilling frack costs are positively correlated with the well's depth.

deep, requires 32 rig-days to drill, and produces 1,100 barrels of oil on the well's first day.

For each well we define several variables which proxy for the well's remoteness, which (we argue) is a proxy for firm j's investment in frontier innovation. While all of the wells in our sample are drilled into the Bakken formation, sub-surface geographic characteristics can vary dramatically from area to area. Therefore, wells fracked in new areas represent greater technical challenges and higher degrees of risk. These investments also provide externalities as other firms gain insights into the economic viability of new fracking techniques in previously un-explore areas. We define the binary $Frontier\,Field_{i,j}$ indicating the first wells to be fracked in a new oil field (as defined by the NDIC). We illustrate an example oil field "Twin Valley" outlined in red in Appendix Figure A4. We show the locations of each $Frontier\,Field_{i,j}$ well fracked in 2006, 2008, 2010, and 2012 in Appendix Figure A5.

For robustness, we define two additional well remoteness measures, which we use in our regressions in addition to $Frontier\,Field_{i,j}$ as proxies for frontier innovation. We also define remoteness as $Frontier\,Grid_{i,j}$ indicating the first wells to be fracked in a new oil 6x6 mile township/range grid as defined by the Public Land Survey System (PLSS). The square-mile blocks, used to define 6x6 mile grid-squares, are visible (numbered) in Appendix Figure A4. Finally, we also observe each well's longitude/latitude, and we calculate $Remote\,Distance_{i,j}$ which is the distance (in miles) of each fracked well i to the nearest fracked well that exists in the data prior to when i was fracked. As we show in Table 1 roughly 3% of the wells in our sample (over 300 wells each) are $Frontier\,Field_{i,j}$ and/or $Frontier\,Grid_{i,j}$ wells. The wells in our sample average a little more than one half mile from the nearest well when they were first fracked as measured by $Remote\,Distance_{i,j}$.

Most of the literature examining innovation relies on firm-level aggregations such as capital spending, R&D spending, patents, and patent citations. However, as shown in Cohen, Nelson, and Walsh (2000), outside of a few industries, such as pharmaceuticals and chemicals, patents are not an effective means by which firms protect new technologies.[9] By contrast, our data allows us to measure innovative investments more directly, and at the project level. In addition, we can also examine different kinds of innovative investments, which we outline below.

In addition to identifying the innovative application of fracking to new areas, we define several variables to proxy for investments in scale innovation. More specifically, we classify wells drilled in multi-well *pads*. Prior to the widespread adoption of fracking, a firm would generally drill a single well, disassemble the drilling rig, move the rig to a new location, and repeat the process. Pad drilling involves drilling multiple wells from a single surface location, which can saves time and money is less environmentally disruptive.[10] We observe the specific drilling rig that drills each well, and we define $Pad2_{i,j}$ indicating well i was one of at least two wells that were drilled in close proximity, by the same firm j, using the same rig, in succession. We define $Pad3_{i,j}$ and $Pad4_{i,j}$ similarly but for groups of three and four or more wells per pad. The map in Appendix Figure A4 shows examples of pads: several lines (horizontal wellbores) extending from tight clusters of black circles (wells).

Finally, we define the variable $Confidential_{i,j,t}$ for wells in which the firm drilling applied with the NDIC for *confidential treatment*. The NDIC requires detailed plans describing the drilling and fracking techniques for each well be filed and made public. This information, as shown in Covert (2015), can be a source of learning for competitors. However, the NDIC allows firms to request confidential treatment, which embargoes the well data for a 6-month period. These competitive concerns primarily include tipping off competitors to productive

[9] Cohen, Nelson, and Walsh (2000) suggest for most industries mechanisms such as secrecy and development lead-times protect against technology appropriation. We believe this is the case for fracking.

[10] See the EIA's "Today in Energy" September, 2012 for a discussion of pads: `https://tinyurl.com/yavnbkoc`.

land assets and safeguarding private technological advancements.[11] Roughly 20% of all wells in our sample get confidential treatment, and we use this data to examine competitive dynamics and information signaling.

3.2. Energy Firm Level Data

Our sample of wells is drilled and fracked by 98 unique energy firms, of which 60 are private and the remaining 38 are public. We summarize the largest of these firms, as measured by the number of wells drilled, in Appendix Table A1. We define the binary variable $Private_{i,j}$ to indicate wells drilled by private firms. We hand-match firm names from the NDIC data to energy firm names from The Center for Research in Security Prices (CRSP), each month, to define which firms are publicly traded. We research each of the 98 companies to ensure we capture names in the NDIC data which relate to operating subsidiaries of public companies. As we show in Table 1, 17% of the wells in our sample were drilled by private companies. We also define $Private_j$ at the firm j level.

Based on our conversations with current and former energy executives, we argue that reserve-based lending is an important source of funds for energy firms investing in fracking. Therefore, we calculate $Reserves_{j,t}$ as the trailing three-year total number of wells drilled, multiplied by the average $Oil\,Production_{i,j}$ for each well, multiplied by the oil price (1-month NYMEX future) from the prior quarter. We argue that this measure is a proxy for the collateral for firm j at quarter t.

In our analysis of mechanisms relating to firm financing constraints, we aggregate our well-level data to a panel of firms j at quarterly t frequency. We define the remoteness and pad variables outlined above in terms of within-firm proportions. Therefore, we define $Frontier\,Field\,Share_{j,t}$ as the share of all wells drilled and fracked by firm j, during quarter t,

[11] See for example https://tinyurl.com/ybxbu5rf.

which were $Frontier\,Field_{i,j}$ wells. We define other *share* variables $Frontier\,Grid\,Share_{i,j}$, $Pad2\,Share_{i,j}$, in a similar manner. As we show in Table 1 on average $Frontier\,Field_{i,j}$ wells represent 10% of the wells drilled for the firms in our sample. The fact that $Frontier\,Field_{i,j}$ wells represent a lower share (3%) of the overall wells in our sample reflects the fact that the largest/most prolific firms in our sample drill a lower share of $Frontier\,Field_{i,j}$ wells. We use the aggregated firm/quarter variables in regressions in which we examine the intensity with which private and public firms invest in frontier and scale innovation.

4. Results

4.1. Frontier Drilling

4.1.1 The First Companies to Frack

We begin our analysis by presenting anecdotal evidence on the propensity of private firms to engage in frontier innovation. In each shale region and oil field, geological differences affect the fracking process and its efficiency (Baihly et al. (2012); Jabbari, Zeng et al. (2012); Saputelli et al. (2014)). The first firm to bring the technology to an area faces a lot of uncertainty over this process. This uncertainty is further compounded by the increased cost of completion of fracked relative to traditional vertical wells.

Private companies were the very first to frack oil wells in North Dakota. The first frack to occur in our data was executed by a small private North Dakota based company called Nance Petroleum during the winter of 2000. Nance has since been acquired by St. Mary Land & Exploration Company, which is now SM Energy: a public company with a $2.4 billion market cap. That first frack involved pumping 147,000 pounds of proppant into a well reaching almost two miles below the surface, and extending three-quarters of a mile horizontally. Over the next three years three more fracks occurred in North Dakota, each performed by a private company. Figure 1 displays the time-series of North Dakota fracks. The top panel shows that in the early part of the sample (2000-2006), private firms comprise the majority (62 out of 110) of the fracked wells. While public companies entered and dramatically increased fracking activity relative to private companies - publics comprise 82% of the massive boom in fracks that occurred in North Dakota between 2007-2016 - private firms remained focused on expanding the geographical frontier of Bakken shale formation. Privates' tendency to "flip" Bakken acreage is summarized by the industry trade publication Platt's (https://tinyurl.com/y9etso2d):

> Their business model is to prove up acreage, drill some great wells, show that the acreage works on a consistent basis and then have some company buy them out... The nature of the beast is not to really ramp up it's just to show that the acreage works consistently.

4.1.2 Expanding the Frontier: Fracking in New Areas

We perform several tests to compare public and private companies' tendencies to perform the first frack in new geographic areas within North Dakota. While all of the wells in our sample are drilled into the Bakken formation, sub-surface geographic characteristics can vary dramatically from area to area. Therefore, wells drilled in new areas represent very different technical challenges, and firms applying fracking techniques to wells drilled a new area face a higher degrees of risk. Given the risks of experimenting with these new technologies to unknown rocks for the first time, and the information externalities that pioneering companies provide to the rest of the industry, we consider fracking in new areas our primary measure of frontier innovation.

Due to the granular nature of our data, we are able to document higher rates of frontier innovation by private firms from multiple different dimensions. Since we lack exogenous variation in firm listing status, the empirical patterns we display below are best interpreted as correlations. However, the robustness of our findings suggest a clear delineation in the type of innovation that privates and publics pursue. Furthermore, in Section 4.3, we assess potential underlying mechanisms for our findings, lending more credence to the results that follow.

First, we measure the rate of frontier innovation using dis-aggregated well-level data by estimating the following regression:

$$Frontier_{i,j} = \beta Private_j + \gamma_{year} + \epsilon_{i,j}. \tag{1}$$

Our three measures of a well's "frontierness", described in Section 3, are $Frontier\ Field_{i,j}$, $Frontier\,Grid_{i,j}$, and $Remote\,Distance_{i,j}$.[12]. We report the results in Table 2. The positive and significant coefficient for $Private_j$ in Columns (1) and (2) of Table 2 indicates that the average well fracked by a private firm is 2.19% more (i.e. almost twice as) likely to be in a new field than the average well fracked by public firm. Qualitatively similar results hold if we define new geographies as 6×6 mile township/range grid-squares (columns (3) and (4)). Private firms enter new grids at at 1.55-2.94% greater frequency than public firms, who drilll only 2.5% of their wells as $Frontier\,Gridi, j$. Using the $Remote\,Distancei, j$ measure (columns (5) and (6)), we find that on average, wells fracked by private firms are located between 0.23-0.44 miles further from any other well than the average well fracked by a public firm.[13] We include year fixed effects to account for the variation in drilling in new areas over the time-series of our sample.

To ensure that our results are not driven by the behavior of a few large firms, we repeat the

[12]We display the time-series of the share of wells denoted as $Frontier\,Field_{i,j}$ in Figure 2

[13]We cluster standard errors at the firm level j to account for correlations due to persistent within-firm characteristics.

above analysis after collapsing our well panel into firm-quarter observations. The outcome variable then becomes $Frontier\,Share_{j,t}$, the share of firm's j wells drilled in quarter t that were drilled on the frontier. We display the results of this analysis in Table 3. We again find that private firms seek out frontier projects at greater frequency. Focusing on our main $Frontier\,Field\,Share_{j,t}$ measure (columns (1) and (2)), we observe that private firms have frontier shares that are between 3.6-5.1% larger than public firms. These difference is economically significant given that the average public firm's frontier share is 7.6%. Columns (3) and (4) depict a qualitatively similar, albeit statistically insignificant increase in private firms' $Frontier\,Grid\,Share_{j,t}$. Finally, the coefficients in columns (5) and (6) indicate that in a given quarter, private firms locate their wells between 0.36-0.61 miles (or 33-56%) further than public firms.

Differences in frontier shares may arise due to the fact that public firms drill many more wells than privates. To rule out this mechanical relationship, we examine whether public entry into new areas lags those of privates. That is, we restrict our sample of wells to only instances in which a firm drills in a field in which it had not previously operated. We denote this sample as the *entry well* sample. By comparing only entry wells, we avoid any mechanical bias in frontier shares that arise from publics drilling many more wells in total. We consider four measures of delayed entry: 1) $Delay\,Time_{j,g}$ - the difference between the drill date of the firm's entry well and the date of the first well ever drilled in the field; 2) $Delay\,Well_{j,g}$ - the number of wells that had been drilled in the field prior to the firm's entry well; 3) $Remote\,Distance_{j,g}$ - the minimum distance between the entry well and any previously existing well (in the field or outside it); and 4) $RemoteoDistance_{j,g}$ - the minimum distance between the entry well and any previously existing well operated by the firm (in the field or outside it). We re-estimate (1) replacing the left-hand-variable with our lag measures and restricting the sample to only entry wells.[14] We report the results in Table 4. We find that on average, private firms enter a new field almost eight months before publics. This time frame amounts to about four additional wells being drilled in the field prior to a public firm's entry. In terms of "remoteness," public firms tend to locate their entry wells over one mile closer to existing operations and about three and a half miles closer to their own operations. Overall, these results suggest that publics choose to wait until fields are better developed before entering new areas.[15] This result, in conjunction with the well and firm-level tests above, suggests private firms more aggressively invest in frontier innovation.

One final concern is that private firm activity represents "fringe" rather than "frontier" drilling. If public firms are simply more judicious and successful in identifying the proper frontier area, then the exploratory work done by private firms should not be considered innovative. To test whether this concern is justified, we estimate the following regression:

$$Boom(Bust)_g = \beta Private_g + \gamma_{year} + \epsilon_g. \tag{2}$$

$Boom_g$ is an indicator that field g is in the top 20% in terms of future development for fields first drilled in the same year. $Bust_g$ is an indicator that field g is in the bottom 20% of future development.[16] We report the results in Table 5. If the frontier investment of private firms is of a systematically poorer quality than that of public firms, we should observe that fields developed by private firms are significantly less likely to become successful booms, significantly more likely to become unsuccessful busts, or both. The results in Table 5 are

[14]We also include an indicator for the firm's first quarter appearing in the data to ensure our results are not driven purely by public firms entering the Bakken shale play later.

[15]Qualitatively similar results obtain if entry is defined at the 6×6 mile township/range grid-squares, although the coefficient on $private_j$ is not statistically significant in the $Delay\,Wells_{j,g}$ specification.

[16]We measure future development as all wells drilled in a field in the four years following the initial well. Qualitatively similar (non-)results obtain if we define busts as fields that saw *no* future development.

not consistent with this hypothesis. Fields initially developed by private firms are no less likely to boom nor are they more likely to bust than those developed by public firms. These (non-)results increase our confidence that the exploratory investment of private companies indeed extends the frontier of viable acreage in North Dakota, i.e. that it serves as frontier innovation.

4.2. Pad Drilling

Having established that private firms invest more intensely in frontier innovation, we proceed to document that public firms overweight investment in scale innovation - i.e. the development of scale-enhancing and cost-reducing technology. The most prominent of such technological advancements is the advent of multi-well pad drilling - the practice of drilling multiple entry points into wells from a single surface location. Pad drilling saves time and money through several different channels. Firstly, pad drilling cuts down on rig assembly and relocation times since rigs don't have to be disassembled and moved several miles to new drill sites. Additionally, pad drilling allows contractors to maximize fluids that assist vertical drilling as one batch, then switch to fluids that assist horizontal drilling without having to clean or remix multiple times. Finally, consolidating drilling sites saves on infrastructure investment such as water, power, and road construction.

Pad drilling cannot be directly observed in the data, but can be inferred with relative ease. To identify pad drilling we follow industry standards (e.g. https://tinyurl.com/yaj6epts) and identify pad wells as any cluster of wells that is drilled sequentially by the same firm-rig pair and within 0.1 miles. Our primary measure of pads includes all qualifying clusters of two or more wells (denoted as $Pad2$).[17]. We choose this threshold because it generates a time-series of pad drilling that resembles estimates consistent with the statistics on pad

[17] We display the time-series of the share of wells denoted as $Pad2_{i,j}$ in Figure 2

drilling generated by DrillingInfo, a premier analytics firm for the E&P industry. However, we also ensure our results are robust to larger cluster size thresholds.

We first confirm that wells drilled within a pad indeed yield drilling efficiencies and cost savings. To do so, we estimate the following regression:

$$Drill\, Days_{i,j} = \beta_1 Pad2_{i,j} + \beta_2' X_{i,j} + \gamma + \epsilon_{i,j} \tag{3}$$

$Drill\, Days_{i,j}$ is the number of days between when the well i was spudded and when total well depth was reached. Our main variable of interest is $Pad2_{i,j}$, an indicator that the well i is part of a pad. We also include a vector of controls $X_{i,j}$ and a vector of fixed effects γ. Our primary controls are the well's horizontal and vertical depth and an indicator for whether the well had multiple laterals (underground branches). We also control for year, field, firm, and rig fixed effects.[18] We present the results of the analysis in Table 6. Our most conservative specification indicates that pad drilling saves on the order of about 1.7 days (column (3)) or about 7% (column (4)) of total drilling times. This estimate is on par with survey-based findings that pad drilling saves about 10% on drilling costs (e.g. https://tinyurl.com/y9aa4brs). At an average daily rate of $18,000 for Bakken rigs, pad drilling saves at least $30,000 per well.[19]

While pad drilling introduces economies of scale, it also requires a firm to commit to a large development plan with multiple wells. The typical pad drilled well has at least 4 wells but could have as many as 25 at one location. Given the capital intense nature of drilling even one well, pad drilling necessitates sufficient access to internal or external sources of capital. As public firms enjoy easier access to financing (Gilje and Taillard (2017)), it is

[18] Our findings are also robust to the inclusion of the firm and rig experience (results unreported).

[19] Note that this is a conservative estimate of cost savings since it does not include time savings from not having to disassemble and relocate the rig, nor does it account for the infrastructure savings.

natural to ask whether they invest more heavily in this type of scale innovation. To answer this question, we estimate the following regression:

$$Pad_{i,j} = \beta_1 Private_j + \gamma_{year} + \epsilon_{i,j,t}. \tag{4}$$

This regression is the natural analog to (1), with the dependent variable representing the propensity to drill multi-well pads. As with our frontier innovation test, we estimate (4) at both the well (Table 7) and firm-quarter (Table 8) levels. The results in Table 7 indicate that, on average, wells drilled by public firms are 10-14% more likely to be part of a multi-well pad than those drilled by private firms. Similarly, the results in Table 8 indicate that, on average, in a given quarter, public firms drill between 5-14% more of their wells using multi-well pads than private firms. As these results indicate that public firms employ multi-well pads at rates 30% higher than private firms, they are consistent with public firms investing more heavily in scale innovation.

Overall, the results in Sections 4.1 and 4.2 suggest that relative to public firms, private firms overweight frontier innovation and underweight scale innovation. These findings are of interest because they suggest that differences in innovation between private and public firms exist not just in terms of the *level* of innovative output generated, but also in the *nature* of the innovative projects that firms pursue. In the subsequent analysis we consider several mechanism by which these differences may arise.

4.3. Mechanisms

In this section, we seek to better understand the mechanisms underlying the results described in Sections 4.1 and 4.2. Specifically, we seek to understand whether the choice of innovation type informs firms' decisions to stay private, or if differences between public and private firms (e.g. access to capital) also affect which innovative projects they pursue. To better illustrate the framework we have in mind, we begin by with a simple exposition of how causality may run from innovation choice to listing choice or vice versa.

Suppose that due to factors such as skill or risk appetite certain managers prefer scale innovation while others prefer frontier innovation. Since public listing status is associated with lower cost of capital, scale innovators would benefit from going public. If contracting frictions preclude the formation of large-scale exploration companies, then frontier innovators have less need for large-scale access to capital. Frontier innovators may then choose to remain private due to either the large fixed cost of going public (Ritter (1987)) or the stricter disclosure requirements for public firms (Farre-Mensa (2017)). In this case, causality runs from innovation to listing status choice. Now suppose that, for reasons such as control rights (Brau and Fawcett (2006); Brav (2009)), certain managers prefer to retain private ownership. These managers will underweight scale innovation as it requires substantial capital to implement. In this case, causality runs from listing status to innovation choice.

Absent exogenous variation in public listing status, it is impossible for us to conclusively determine the direction of causality. However, we are able to provide several pieces of suggestive evidence. Our tests focus on two possible channels. The first is that financial constraints lead private firms to overweight frontier and underweight scale innovation - i.e. that listing choice affects innovation choice. The second is that firms who specialize in frontier innovation choose to remain private due to disclosure requirements - i.e. that innovation choice affects listing choice. As we show below, our evidence is more consistent with the financing channel.

4.3.1 Financial Constraints

The main distinction between the two hypotheses posited above is that if causality runs from innovation to listing choice, we should not expect firms to change their behavior following a relaxation in financing constraints. Two critical features in our empirical framework provide us with an opportunity to test this prediction. The first feature is that private firms rely heavily on reserve base lending (RBL, see Azar (2017)) - loans collateralized by existing proven producing, non-producing, and undeveloped reserves - while public firms do so to a much lower degree. The second feature is that we observe the complete (within North Dakota) production history for our set of firms, which allows us to construct estimates for past corporate cash flows as well as current production reserves. We leverage these aspects of our data to construct a test that gauges whether the private firms exhibit differential (relative to public) sensitivities to changes in their borrowing capacity (i.e. their reserve base). Specifically, we estimate the following two regressions:

$$Frontier\,Share_{j,t} = \beta_1 Private_j + \beta_2 Reserve_{j,t} + \beta_3 Private_j \times Reserve_{j,t} + \gamma_j + \epsilon_{j,t} \quad (5)$$

$$Pad\,Share_{j,t} = \beta_1 Private_j + \beta_2 Reserve_{j,t} + \beta_3 Private_j \times Reserve_{j,t} + \gamma_j + \epsilon_{j,t} \quad (6)$$

We define $\text{Reserve}_{j,t}$ in Section 3.2. The coefficient of interest is β_3, which measures whether private firms exhibit more acute changes in behavior in response to changes in their reserve base. We report the results for (5) and (6) in Tables 9 and 10 respectively. The negative (positive) and significant β_3 coefficient in column (3) of Table 9 (10), indicate that on average, an increase of \$10 million in our reserve measure is associated with a decrease of 14 basis points (increase of 52 basis points) in frontier (scale) innovation shares for private firms. The same \$10 million increase in $\text{Reserve}_{j,t}$ is associated with only a 0.5 basis point reduction

(20 basis point increase) in frontier (scale) innovation shares for public firms. This effect represents a 1.1% reduction (2% increase) relative to the average private firm's frontier (pad) share. These findings are consistent with the hypothesis that private firms underweight scale and overweight frontier innovation due to financial constraints.

The identifying assumption in these tests are that any incremental effect of $Reserve_{j,t}$ for private firms obtains solely via the relaxation of borrowing constraints. We believe that $Reserve_{j,t}$ is a much stronger determinant of financial capacity for private firms than public ones for two reasons. The first is the privates rely on RBL to a much higher degree than public firms. The second is that the private firms in our data are much more likely to operate solely in the Bakken formation, meaning our $Reserve_{j,t}$ measure is a much better proxy for their aggregate collateral base than it is for public firms. Of course, our measure may also be correlated with confounding factors. While we cannot rule out alternative explanations in general, we provide several arguments to validate our identifying assumption. First, to account for the fact that firms with larger or smaller reserve base may differ along dimensions such as managerial preferences or risk appetite, we estimate (5) and (6) using firm fixed effects. This specification identifies the β_3 coefficient by examining within-firm changes in response to variation in its collateral base. If causality runs from innovation to listing choice, we should not expect to observe these within-firm responses, and so it is comforting that our results obtain even with the inclusion of firm fixed effects. Secondly, we note that while $Reserve_{j,t}$ may capture factors beyond just the collateral base, e.g. accrual of experience, our interpretation holds as long as any correlation between $Reserve_{j,t}$ and other observables does not differ across public and private firms. Finally, we note that asset base is a well-known determinant of financial capacity. In fact, in a similar setting to ours, Gilje and Taillard (2017) use well base as a measure of financial capacity for private firms and show that firms with bigger collateral bases act in a less constrained manner.

4.3.2 Disclosure

The results above suggest higher costs of capital lead private firms to overweight frontier and underweight scale innovation. These findings are inconsistent with the notion that causality runs from innovation choice to listing status choice. We perform one additional test to gauge whether disclosure requirements lead firms engaged in frontier innovation to remain private. To assess this possibility, we estimate the following regression:

$$Confidential_{i,j} = \beta Private_j + \gamma_{year} + \epsilon_{i,j}. \tag{7}$$

Where $Confidential_{i,j}$ is an indicator that the well was filed under confidential status. We present the results of this test in Table 11. If frontier innovative firms are worried about disclosure to competitors, they should also avail themselves of the confidential well filing with higher frequency than other firms. The results from estimating (7) are inconsistent with this explanation. The coefficient on $Private_j$ is negative, albeit statistically insignificantly so, suggesting that if anything, private firms are less likely to petition for confidential status.[20] Importantly, in column (3) of Table 11 we verify that privates are no more secretive regarding their frontier investments. While this finding cannot completely reject the hypothesis that firms first choose innovation type and then choose listing status, it at least rejects the notion that frontier innovators remain private due to disclosure reasons.

[20]Unconditionally, about 20% of wells in our sample were filed confidentially. Given that there are no significant costs for petitioning for confidential well status, one may wonder why all wells are not filed confidentially. One potential reason is that firms may be worried that overuse of this tool may lead regulatory agencies to crack down on it - see for example https://tinyurl.com/ybxbu5rf.

5. Conclusion

We use detailed micro-data on oil well drilling in North Dakota to examine differences in innovation between private and public firms. Rather than focus on the *level* of innovation, we analyze whether private and public firms engage in different *types* of innovation. We focus on two complementary yet distinct forms of innovative investment: 1) the discovery and adaptation of new technologies (frontier innovation) and 2) implementing new technological discoveries on a large scale and in a cost-efficient manner (scale innovation). We find that private (public) firms overweight investment in frontier (scale) innovation and link our findings to differential access to capital markets.

Since we lack exogenous variation in listing status our analysis is inherently descriptive. However, we believe that our approach - that is focusing on the nature of innovative activity and relying on detailed data beyond patents - provides an important contribution to the literature's understanding on how private and public firms innovate. Further developing this intuition and more concretely identifying the underlying mechanism is a promising area for future work.

Appendix A: Supporting Data

Table A1: Individual Company Summary Statistics

In this table we present summary statistics for the most active of the 98 firms in our sample. Our sample of 11,313 oil wells i and firms j spans 2000-2016. We define all variables in Section 3. The data are from the North Dakota Industrial Commission and CRSP.

Firm Name	Private_j	Total Wells Fracked	Total Frontier $\text{Field}_{i,j}$	Frontier Field $\text{Share}_{j,t}$	Total $\text{Pad2}_{i,j}$	Pad2 $\text{Share}_{j,t}$
CONTINENTAL RESOURCES, INC.	0	1195	36	0.03	638	0.53
HESS	0	1146	25	0.02	796	0.69
WHITING OIL AND GAS CO	0	1025	21	0.02	493	0.48
EOG RESOURCES, INC.	0	711	11	0.02	253	0.36
XTO ENERGY INC.	0	639	3	0.00	527	0.82
BURLINGTON RESOURCES	0	595	18	0.03	397	0.67
OASIS PETROLEUM	0	583	11	0.02	358	0.61
MARATHON OIL COMPANY	0	516	7	0.01	269	0.52
STATOIL OIL & GAS LP	0	460	2	0.00	373	0.81
PETRO-HUNT, L.L.C.	1	347	13	0.04	184	0.53
KODIAK OIL & GAS (USA) INC.	0	331	7	0.02	265	0.80
QEP ENERGY COMPANY	0	315	0	0.00	292	0.93
SLAWSON EXPLORATION CO	1	278	5	0.02	160	0.58
NEWFIELD PRODUCTION CO	0	262	10	0.04	179	0.68
SM ENERGY COMPANY	0	251	5	0.02	154	0.61
OXY USA INC.	0	188	2	0.01	98	0.52
FIDELITY E&P CO	1	157	5	0.03	29	0.18
SAMSON RESOURCES COMPANY	0	152	8	0.05	108	0.71
WPX ENERGY WILLISTON, LLC	0	152	0	0.00	137	0.90
HUNT OIL COMPANY	1	145	5	0.03	28	0.19
BRIGHAM OIL & GAS, L.P.	0	138	19	0.14	42	0.30
ZENERGY, INC	1	135	6	0.04	21	0.16
TRIANGLE USA PETROLEUM CO	0	120	1	0.01	105	0.88
ZAVANNA, LLC	1	110	4	0.04	54	0.49
MUREX PETROLEUM CO	1	96	7	0.07	0	0.00

Figure A1: Crude Oil Prices and the North Dakota Fracking Boom

In the top panel we show the price for West Texas Intermediate (WTI) Crude Oil at the Midland, TX hub as reported by the EIA. In the second panel we show the number of oil wells drilled in North Dakota, as well as the share of wells (by year) of wells that were fracked upon completion. The data come from the North Dakota Industrial Commission for wells drilled between 2000-2016.

WTI Crude Oil Price ($/barrel)

Wells Drilled (bars, left scale) **Share Fracked (line, right scale)**

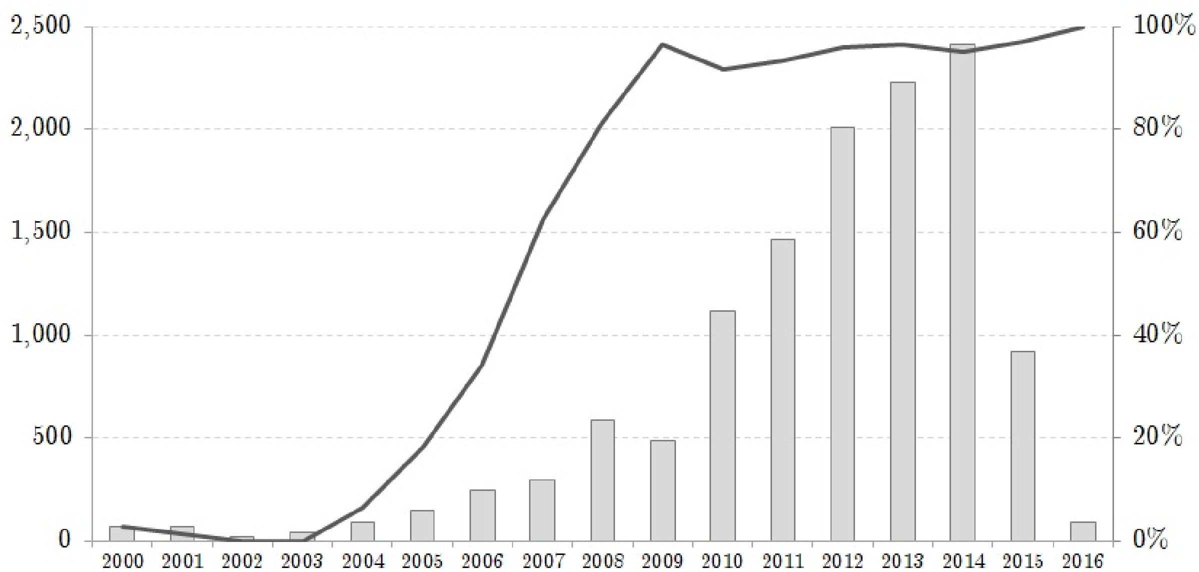


Figure A2: North Dakota Well Production

In this figure we show the average oil production of oil wells drilled in each year in North Dakota. The solid bars indicate production from non-fracked wells, and the striped bars indicate production from fracked wells. The data come from our sample of 11,313 oil which were drilled and fracked, as well as 1,845 oil wells which were drilled but not fracked, between 2000-2016. The data for both fracked and non-fracked oil wells come from the North Dakota Industrial Commission.

Oil Production (first 24 hours, barrels)

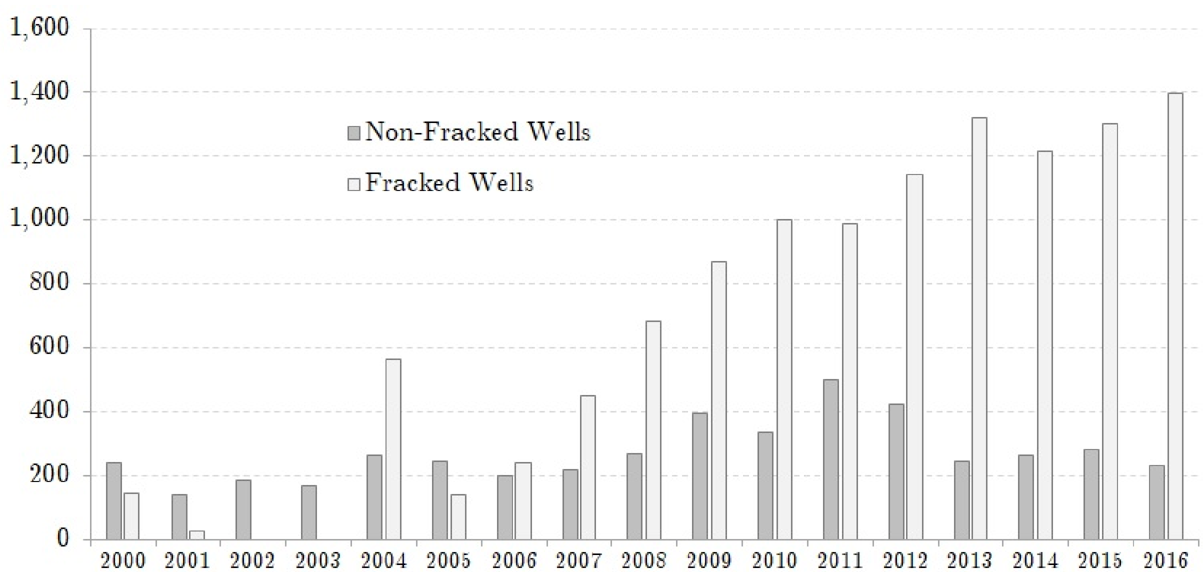
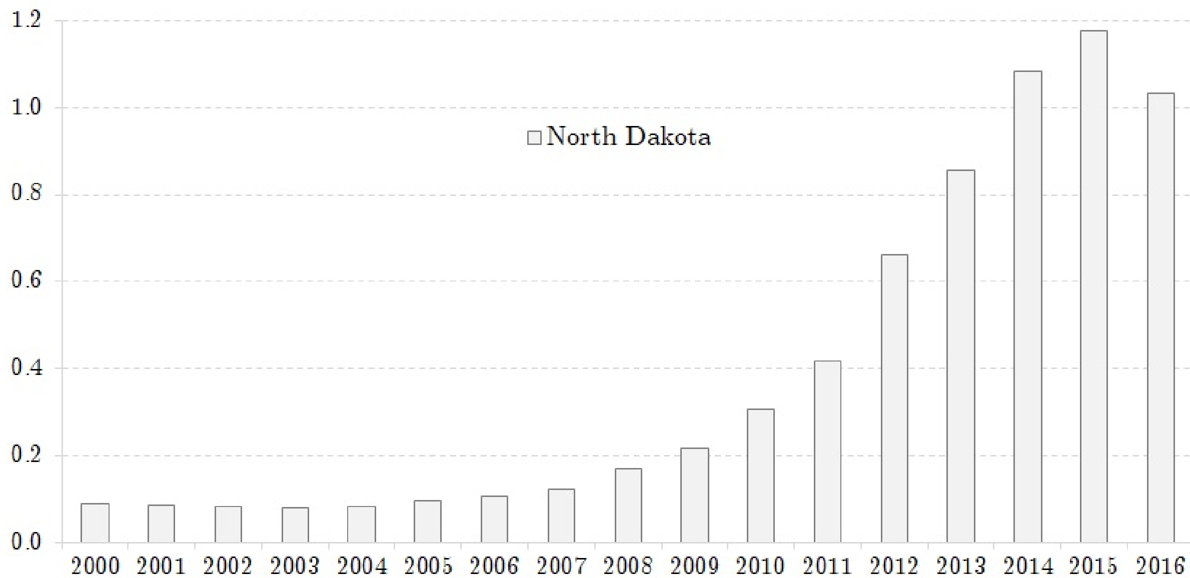


Figure A3: Trends in United States Crude Oil Production, Imports, and Exports

In the top panel we show the trend in the aggregated crude oil production (average barrels/day) for the state of North Dakota. In the bottom panel we show the trend in the aggregated crude oil production (average barrels/day) for the United States. We show the shares coming from North Dakota and Texas which is where oil fracking has been most prevalent. The data come from the Energy Information Agency.

Total Crude Oil Production: North Dakota (Mln barrels/day)



Crude Oil Production: Total United States (Mln barrels/day)

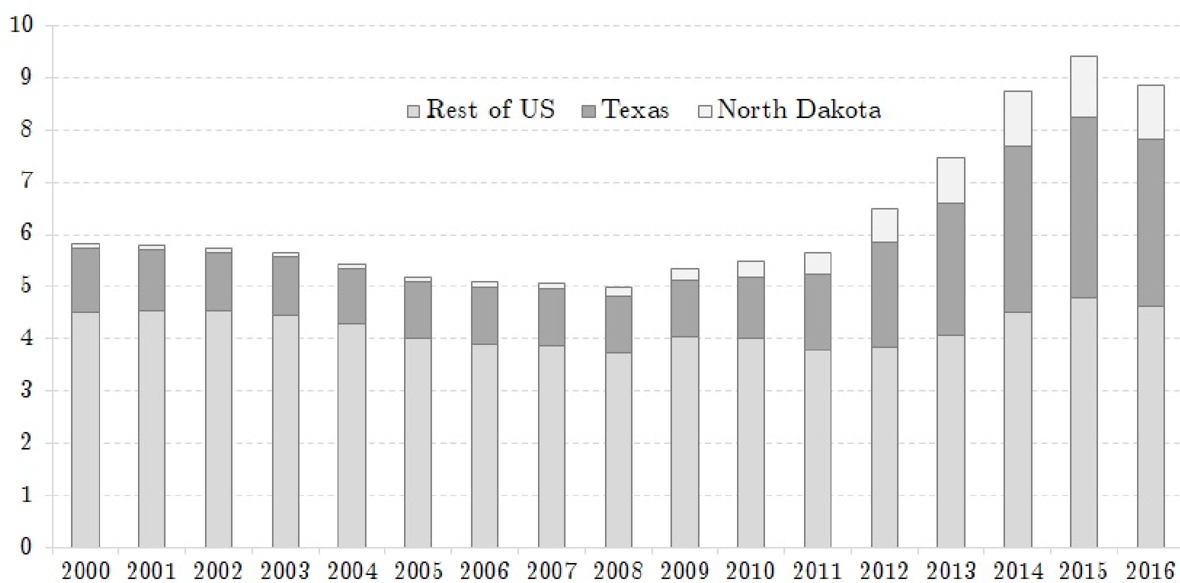


Figure A4: North Dakota Oil Field Map Sample

In this figure we show an image capture from the North Dakota Industrial Commission oil well map server. The red outlines indicate oil fields ("Twin Valley" is an oil field), and the numbered squares are square mile-blocks as indicated by the Public Land Survey System. The black circular dots are oil wells, and the lines extending from the dots indicate subterranean oil-well laterals that extend horizontally. The image represents roughly 24 square-miles.

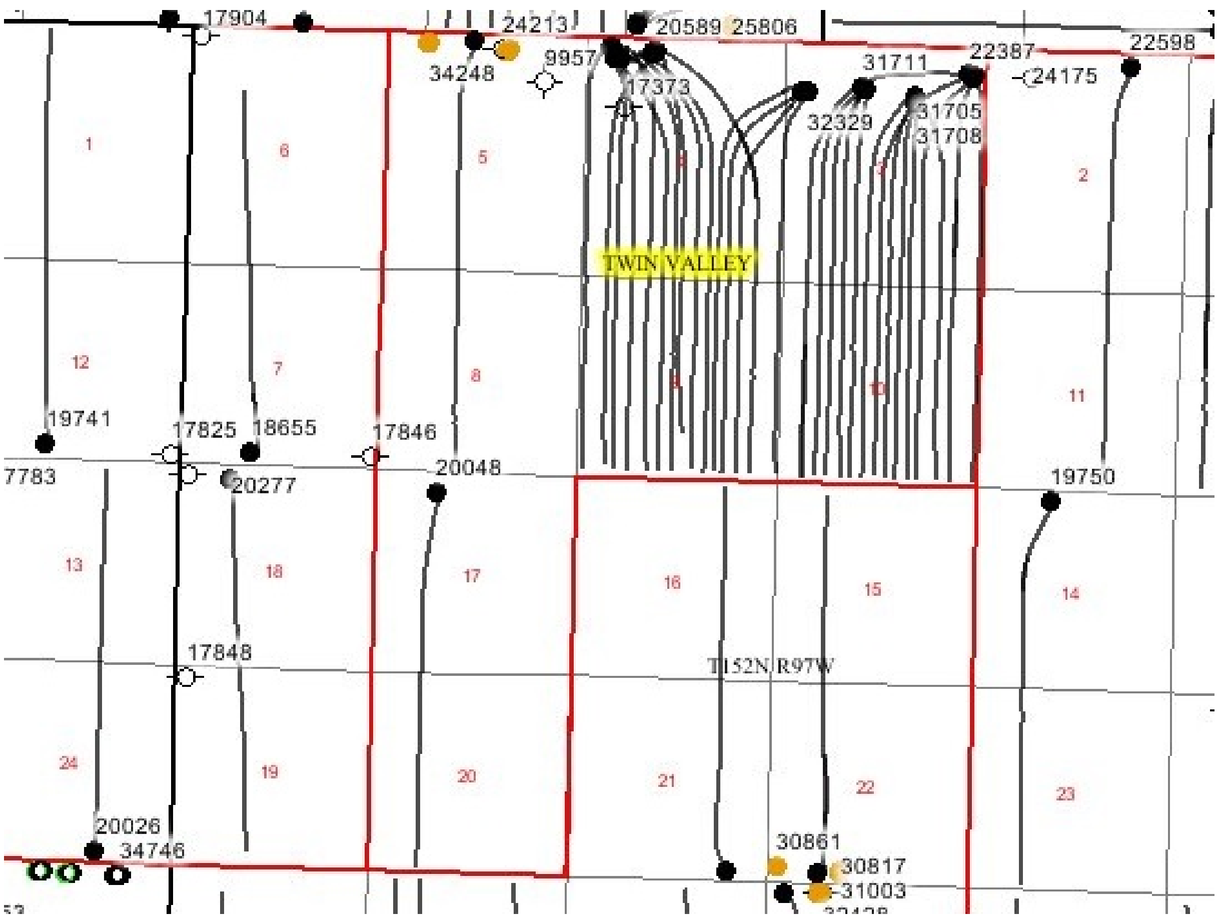


Figure A5: North Dakota Frontier Wells Over Time

In this figure we show the trend in Bakken oil wells drilled and fracked in North Dakota. Each panel shows a map of all oil wells drilled and fracked in North Dakota as of the end of each indicated year. Red dots represent Frontier Field$_{i,j}$ wells drilled and fracked in the respective year. Blue dots represent all other new oil wells drilled and fracked in that year, and black dots represent all oil wells drilled prior to that year. The data come from the North Dakota Industrial Commission.

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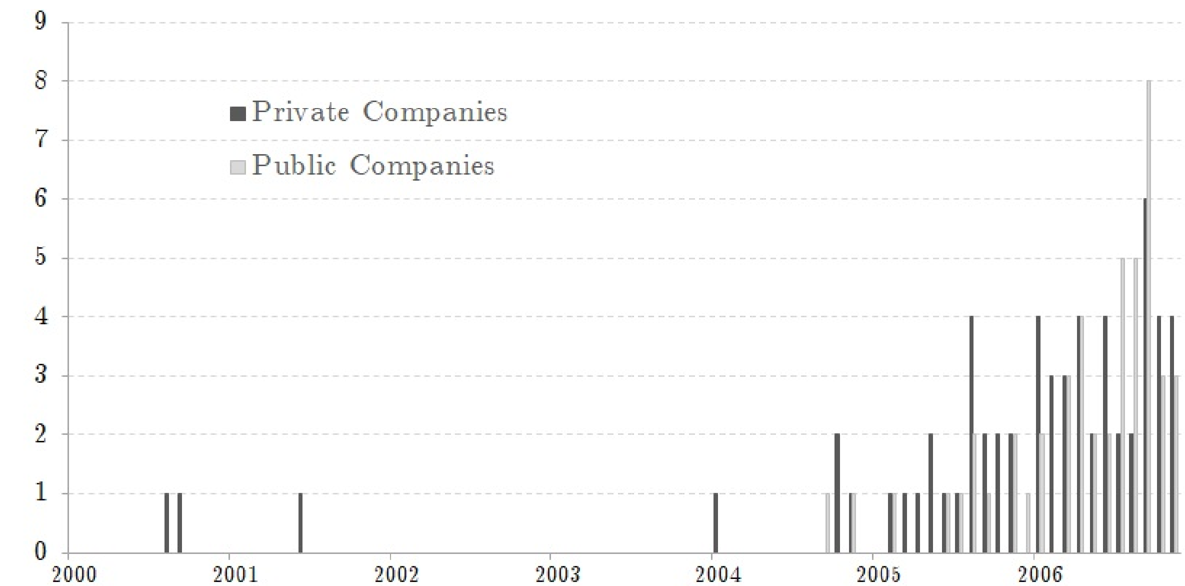
Figure 1: Fracking by Private and Public Companies

In the top panel we show the number of fracks (we define fracking in Section 2) performed in North Dakota over the early part of our sample for both private companies and public companies. In the bottom panel we show the number of fracks performed in North Dakota over our entire sample: 2000-2016. The data come from the North Dakota Industrial Commission.

Number of Fracks



Number of Fracks

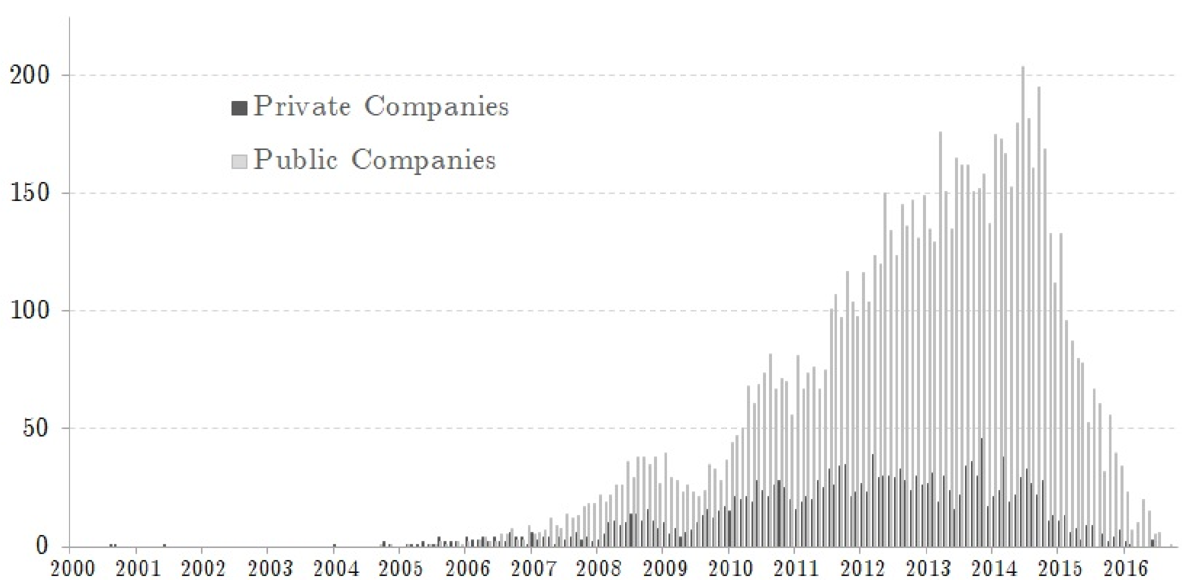
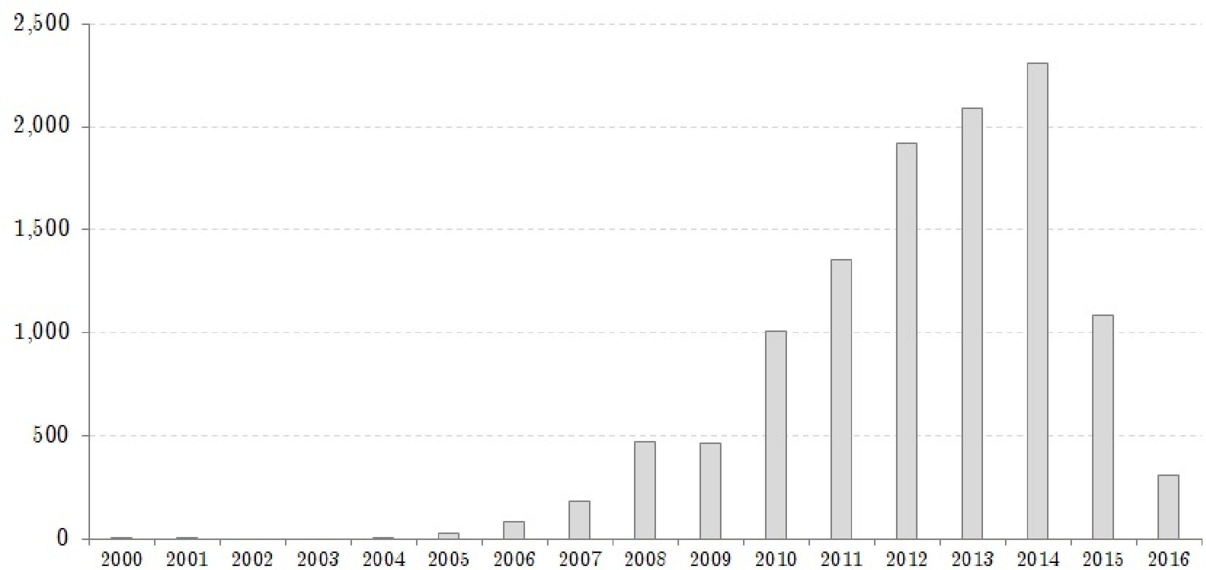


Figure 2: Trends in Fracking, Frontier Fracking, and Pad Drilling in North Dakota

In the top panel we show the trend in the number of fracks in North Dakota. In the bottom panel we show the trends in the share of Frontier Field$_{i,j}$ fracks as a share of all fracks, and the trend in Pad2$_{i,j}$ fracks as a share of all fracks. We define these variables in Section 3. The data come from the North Dakota Industrial Commission.

Total Crude Number of Fracks



Share of Fracks

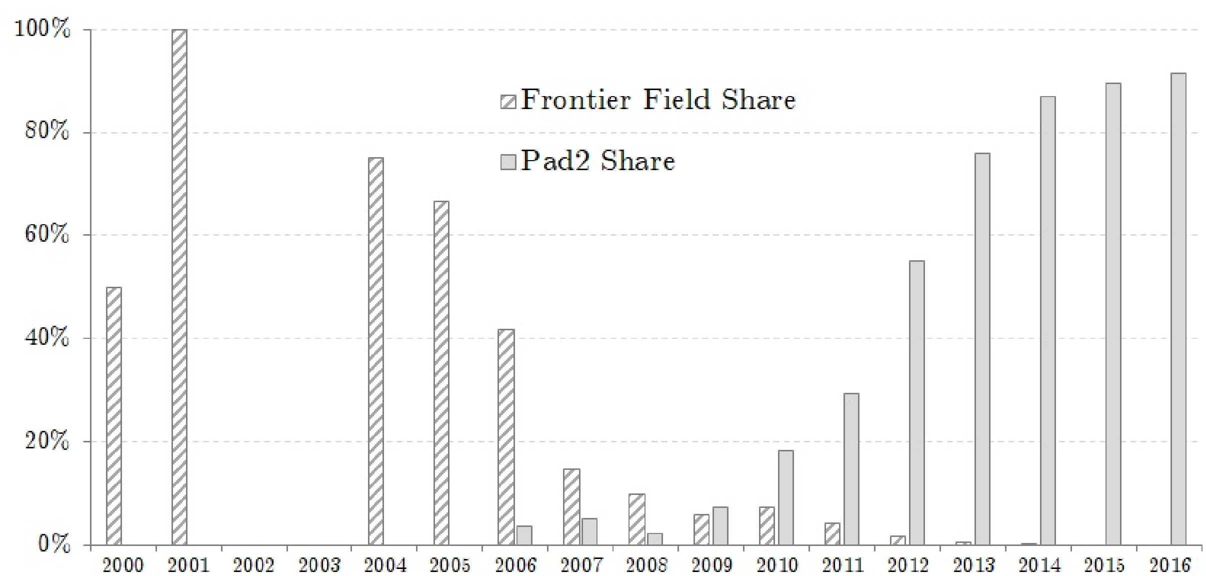


Table 1: Summary Statistics

In this table we present summary statistics for our samples of 11,313 oil wells i drilled and fracked by 98 firms j in North Dakota between 2000-2016. We define all variables in Section 3. The data are from the North Dakota Industrial Commission and CRSP. The below summary statistics reflect the pooled sample of all 11,313 wells as well as variables aggregated at the operator j and quarter t level.

	Mean	Median	Std Dev	Min	Max	n
Well Level Data:						
Private$_{i,j}$	0.17	0.00	0.37	0.00	1.00	11,313
Total Depth$_{i,j}$	3.74	3.86	0.38	0.35	5.14	11,313
Oil Production$_{i,j}$	1,128.35	901.00	827.60	0.00	6,002	11,177
Drill Days$_{i,j}$	32.09	28.00	36.78	1.00	2,958	11,269
Frontier Field$_{i,j}$	0.03	0.00	0.17	0.00	1.00	11,313
Frontier Grid$_{i,j}$	0.03	0.00	0.17	0.00	1.00	11,313
Remote Distance$_{i,j}$	0.57	0.12	1.41	0.00	66.90	11,312
Pad2$_{i,j}$	0.58	1.00	0.49	0.00	1.00	11,313
Pad3$_{i,j}$	0.38	0.00	0.49	0.00	1.00	11,313
Pad4$_{i,j}$	0.24	0.00	0.43	0.00	1.00	11,313
Confidential$_{i,j}$	0.20	0.00	0.40	0.00	1.00	11,313
Firm Level Data:						
Private$_{j}$	0.39	0.00	0.49	0.00	1.00	1,173
Frontier Field Share$_{j,t}$	0.10	0.00	0.25	0.00	1.00	1,173
Frontier Grid Share$_{j,t}$	0.10	0.00	0.26	0.00	1.00	1,173
Remote Distance$_{j,t}$	1.33	0.64	3.20	0.00	66.90	1,173
Pad2 Share$_{j,t}$	0.39	0.22	0.41	0.00	1.00	1,173
Pad3 Share$_{j,t}$	0.22	0.00	0.35	0.00	1.00	1,173
Pad4 Share$_{j,t}$	0.13	0.00	0.27	0.00	1.00	1,173
Reserves$_{j,t}$	7.40	1.98	12.24	0.00	84.85	1,173

Table 2: Fracking in New Areas - Well Level

In this table we present regressions examining the propensity to frack in new areas with our sample of well-level data. We measure new areas using three variables: 1) Frontier Field$_{i,j}$ which indicates well i drilled by firm j is the first fracked well in an oil field as defined by the North Dakota Industrial Commission; 2) Frontier Grid$_{i,j}$ which indicates well i drilled by firm j is the first fracked well in a 6×6 mile township/range grid-square; 3) Remote Distance$_{i,j}$ is the minimum distance, in miles, from well i to all other fracked wells. The independent variable of interest is Private$_j$ a dummy variable indicating firm j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3. We multiply the dependent variables (save for Remote Distance) by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Frontier Field$_{i,j}$	(2) Frontier Field$_{i,j}$	(3) Frontier Grid$_{i,j}$	(4) Frontier Grid$_{i,j}$	(5) Remote Distance$_{i,j}$	(6) Remote Distance$_{i,j}$
Private$_j$	3.57***	2.19**	2.94***	1.55**	0.44***	0.23***
	(3.12)	(2.44)	(2.82)	(1.99)	(3.42)	(3.11)
Intercept	2.36***		2.51***		0.49***	
	(7.47)		(7.35)		(12.31)	
Year FE	No	Yes	No	Yes	No	Yes
Cluster Errors	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$
Observations	11,313	11,312	11,313	11,312	11,312	11,310
R^2	0.006	0.117	0.004	0.155	0.013	0.346

Table 3: Fracking in New Areas - Firm Level

In this table we present regressions examining the propensity to frack in new areas using data aggregated into a panel of firms (j) at quarterly (t) frequency. We measure new areas using three variables: 1) Frontier Field Share$_{j,t}$ the share of wells drilled by firm j in an oil field as defined by the North Dakota Industrial Commission during quarter t; 2) Frontier Grid Share$_{j,t}$ the share of wells drilled by firm j which are the first to be fracked in a 6×6 mile township/range grid-square during quarter t; 3) Remote Distance$_{j,t}$ is the average minimum distance, in miles, from well i to all other fracked wells, drilled by firm j during quarter j. The independent variable of interest is Private$_j$ a dummy variable indicating firm j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3 aggregated into a panel at the firm (j) level at quarterly (t) frequency. We multiply the dependent variables (save for Remote Distance) by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Frontier Field Share$_{j,t}$	(2) Frontier Field Share$_{j,t}$	(3) Frontier Grid Share$_{j,t}$	(4) Frontier Grid Share$_{j,t}$	(5) Remote Distance$_{j,t}$	(6) Remote Distance$_{j,t}$
Private$_j$	5.095**	3.642*	2.576	1.043	0.609**	0.360**
	(2.08)	(1.84)	(1.14)	(0.61)	(2.22)	(2.13)
Intercept	7.621***		9.410***		1.091***	
	(6.51)		(7.14)		(9.80)	
Year FE	No	Yes	No	Yes	No	Yes
Cluster Errors	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$	Firm$_j$
Observations	1,173	1,171	1,173	1,171	1,173	1,171
R^2	0.010	0.295	0.002	0.364	0.009	0.426

Table 4: Fracking in New Areas - Entry Wells

In this table we present regressions examining the characteristics of "entry wells" for private and public firms. We define entry wells as a firm's first well in an oil field g as defined by the North Dakota Industrial Commission. Delay $\text{Time}_{j,g}$ is the difference between the firm's entry well drill date and the date of the first well ever drilled in the field. Delay $\text{Well}_{j,g}$ is the number of wells that had been drilled in the field prior to the entry well. Remote $\text{Distance}_{j,g}$ is the minimum distance, in miles, from the entry well to all other previously fracked well. Remote $\text{oDistance}_{j,g}$ is the minimum distance, in miles, from the entry well to any other well fracked by the firm. The independent variable of interest is Private_j a dummy variable indicating firm j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Delay $\text{Time}_{j,g}$	(2) Delay $\text{Well}_{j,g}$	(3) Remote $\text{Distance}_{j,g}$	(4) Remote $\text{oDistance}_{j,g}$
Private_j	-228.328***	-3.891*	1.011***	3.476**
	(2.207)	(-1.787)	(2.897)	(2.099)
Year FE	Yes	Yes	Yes	Yes
1st Data FE	Yes	Yes	Yes	Yes
Cluster Errors	Firm_j	Firm_j	Firm_j	Firm_j
Observations	1,062	1,062	1,062	993
R^2	0.398	0.237	0.382	0.121

Table 5: Boom and Bust of Developed Areas

In this table we present regressions examining the likelihood a field is a boom or a bust. In Columns 1 - 2 $Boom_g$ is an indicator equal to 1 if the field is in the the top 20% of well drilling 12 - 48 months after the initial well compared to other fields which began production in the same year. In Columns 3 - 4 $Bust_g$ is an indicator equal to 1 if the field is in the the bottom 20% of well drilling in the 48 months after the initial well compared to other fields which began production in the same year. The independent variable of interest is Private_g a dummy variable indicating the field was first drilled by a private firm. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Boom_g	(2) Boom_g	(3) Bust_g	(4) Bust_g
Private_g	-2.752	-2.837	0.632	0.526
	(-0.568)	(-0.563)	(0.126)	(0.104)
Intercept	22.170***		21.698***	
	(7.746)		(7.640)	
Year FE	No	Yes	No	Yes
Observations	315	315	315	315
R^2	0.001	0.002	0.000	0.004

Table 6: Pad Drilling Efficiency

In this table we present regressions examining the determinants of well drill times. Drill $\text{Days}_{i,j}$ is the number of days from the well i's drill date to the date in which the well's total depth was reached. The independent variable of interest is $\text{Pad2}_{i,j}$ an indicator that the well was drilled as part of a multi-well pad. $\text{HDepth}_{i,j}$ is the horizontal depth of the well. $\text{VDepth}_{i,j}$ is the vertical depth of the well. $\text{Laterals}_{i,j}>1$ is an indicator that the well has multiple laterals. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Drill $\text{Days}_{i,j}$	(2) Drill $\text{Days}_{i,j}$	(3) Drill $\text{Days}_{i,j}$	(4) ln(Drill $\text{Days}_{i,j}$)
$\text{Pad2}_{i,j}$	-6.498***	-6.576***	-1.708***	-0.070***
	(-9.934)	(-11.032)	(-3.209)	(-6.844)
$\text{HDepth}_{i,j}$		3.945***	4.863***	0.139***
		(7.830)	(10.974)	(14.486)
$\text{VDepth}_{i,j}$		0.311	0.329	0.006
		(0.794)	(0.935)	(0.694)
$\text{Laterals}_{i,j}>1$		13.539***	10.633**	0.193*
		(3.948)	(2.566)	(1.877)
Intercept	35.067***	26.353***		
	(37.402)	(16.977)		
Year FE	No	No	Yes	Yes
Firm FE	No	No	Yes	Yes
Field FE	No	No	Yes	Yes
Rig FE	No	No	Yes	Yes
Cluster Errors	Firm_j	Firm_j	Firm_j	Firm_j
Observations	11,186	11,186	11,186	11,186
R^2	0.038	0.079	0.380	0.387

Table 7: Pad Drilling and Fracking - Well Level

In this table we present regressions examining the propensity to drill and frack wells in multi-well pads, which we describe in Section 3 and illustrate in Figure 2. We define pads in three ways: 1) $\text{Pad2}_{i,j}$ indicates wells drilled by operator j in which two or more wells share the same pad; 2) $\text{Pad3}_{i,j}$ indicates wells drilled by operator j in which three or more wells share the same pad; and 3) $\text{Pad4}_{i,j}$ indicates wells drilled by operator j in which four or more wells share the same pad. The independent variable of interest is Private_j a dummy variable indicating firm j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) $\text{Pad2}_{j,t}$	(2) $\text{Pad2}_{j,t}$	(3) $\text{Pad3}_{j,t}$	(4) $\text{Pad3}_{j,t}$	(5) $\text{Pad4}_{j,t}$	(6) $\text{Pad4}_{j,t}$
Private_j	-21.76***	-12.75**	-22.39***	-13.87***	-15.63***	-9.70***
	(-3.05)	(-2.61)	(-3.43)	(-3.49)	(-3.30)	(-2.90)
Intercept	61.44***		41.85***		26.54***	
	(16.50)		(9.88)		(7.78)	
Year FE	No	Yes	No	Yes	No	Yes
Cluster Errors	Firm_j	Firm_j	Firm_j	Firm_j	Firm_j	Firm_j
Observations	11,313	11,312	11,313	11,312	11,313	11,312
R^2	0.027	0.382	0.029	0.335	0.019	0.210

Table 8: Pad Drilling and Fracking - Firm Level

In this table we present regressions examining the propensity to drill and frack wells in multi-well pads, which we describe in Section 3 and illustrate in Figure 2. We define pads in three ways: 1) Pad2 $\text{Share}_{j,t}$ the share of wells drilled by operator j during quarter t which two or more wells share the same pad; 2) Pad3 $\text{Share}_{j,t}$ the share of wells drilled by operator j during quarter t which three or more wells share the same pad; and 3) Pad4 $\text{Share}_{j,t}$ the share of wells drilled by operator j during quarter t which four or more wells share the same pad. The independent variables of interest is Private_j a dummy variable indicating operator j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3 aggregated into a panel at the operator (j) level at quarterly (t) frequency. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Pad2 $\text{Share}_{j,t}$	(2) Pad2 $\text{Share}_{j,t}$	(3) Pad3 $\text{Share}_{j,t}$	(4) Pad3 $\text{Share}_{j,t}$	(5) Pad4 $\text{Share}_{j,t}$	(6) Pad4 $\text{Share}_{j,t}$
Private_j	-21.147***	-14.624***	-17.663***	-11.686***	-9.602***	-5.386**
	(-3.87)	(-3.55)	(-3.94)	(-3.60)	(-2.89)	(-2.11)
Intercept	47.244***		28.576***		16.703***	
	(14.42)		(9.19)		(7.25)	
Year FE	No	Yes	No	Yes	No	Yes
Cluster Errors	Firm_j	Firm_j	Firm_j	Firm_j	Firm_j	Firm_j
Observations	1,173	1,171	1,173	1,171	1,173	1,171
R^2	0.062	0.552	0.062	0.503	0.031	0.362

Table 9: Fracking and Reserves

In this table we present regressions examining a firm's propensity to frack in new areas and a firm's reserves. We measure new areas using Frontier Field $\text{Share}_{j,t}$ which is the share of wells drilled by firm j in an oil field as defined by the North Dakota Industrial Commission during quarter t. The independent variables of interest are $\text{Reserves}_{j,t}$ our proxy for firm reserves which we describe in Section 3.2; Private_j which is a dummy variable indicating firm j is a private company, and the interaction of these variables. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3 aggregated into a panel at the firm (j) level at quarterly (t) frequency. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Frontier Field $\text{Share}_{j,t}$	(2) Frontier Field $\text{Share}_{j,t}$	(3) Frontier Field $\text{Share}_{j,t}$
Private_j	0.036*	0.053*	
	(1.84)	(1.91)	
$\text{Reserves}_{j,t}$		-0.000	-0.005***
		(-1.14)	(-3.82)
$\text{Private}_j \times \text{Reserves}_{j,t}$		-0.008**	-0.009***
		(-2.03)	(-2.98)
Year FE	Yes	Yes	No
Firm FE	No	No	Yes
Cluster Errors	Firm_j	Firm_j	Firm_j
Observations	1,171	1,171	1,163
R^2	0.295	0.299	0.245

Table 10: Pad Drilling and Reserves

In this table we present regressions examining a firm's propensity to drill and frack wells in multi-well pads and a firm's reserves. We define a firm's propensity to drill in pads as: Pad2 Share$_{j,t}$ the share of wells drilled by operator j during quarter t which two or more wells share the same pad. The independent variables of interest are are Reserves$_{j,t}$ our proxy for firm reserves which we describe in Section 3.2; Private$_j$ which is a dummy variable indicating firm j is a private company, and the interaction of these variables. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3 aggregated into a panel at the firm (j) level at quarterly (t) frequency. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) Pad2 Share$_{j,t}$	(2) Pad2 Share$_{j,t}$	(3) Pad2 Share$_{j,t}$
Private$_j$	-0.146***	-0.146***	
	(-3.55)	(-3.46)	
Reserves$_{j,t}$		0.003*	0.020***
		(1.91)	(7.70)
Private$_j$×Reserves$_{j,t}$		0.009*	0.032***
		(1.67)	(5.10)
Year FE	Yes	Yes	No
Firm FE	No	No	Yes
Cluster Errors	Firm$_j$	Firm$_j$	Firm$_j$
Observations	1,171	1,171	1,163
R^2	0.552	0.561	0.558

Table 11: Private Firms and Confidentiality Status

In this table we present regressions examining the likelihood a firm files for confidential stats for a well. $\text{Confidential}_{i,j}$ is an indicator that confidential status was filed for the well. $\text{Frontier Field}_{i,j,t}$ is an indicator that the well is the first in the field. $\text{Oil Production}_{i,j}$ is the initial oil production test of the well in thousands of gallons. The independent variable of interest is Private_j an indicator that firm j is a private company. The data are our sample of all Bakken wells drilled and fracked in North Dakota from 2000-2016 as described in Section 3. We multiply the dependent variables by 100 for coefficient readability. We present T-statistics in parenthesis: *** indicates significance at 1% level, ** indicates 5%, and * indicates 10%.

	(1) $\text{Confidential}_{i,j}$	(2) $\text{Conf}_{i,j}$	(3) $\text{Conf}_{i,j}$	(4) $\text{Conf}_{i,j,t}$
Private_j	-3.944	-5.461	-5.300	-2.923
	(-0.483)	(-0.664)	(-0.627)	(-0.303)
$\text{Frontier Field}_{i,j,t}$			1.235	
			(0.307)	
$\text{Private}_j \times \text{Frontier Field}_{i,j}$			-3.476	
			(-0.486)	
$\text{Oil Production}_{i,j}$				0.252
				(0.068)
$\text{Private}_j \times \text{Oil Production}_{i,j}$				-3.551
				(-0.755)
Intercept	20.307***			
	(3.465)			
Year FE	No	Yes	Yes	Yes
Observations	11,305	11,305	11,305	11,173
Cluster Errors	Firm_j	Firm_j	Firm_j	Firm_j
R^2	0.001	0.140	0.140	0.136