



Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Effects of stricter environmental regulations on resource development[☆]

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ARTICLE INFO

Article history:

Received 26 April 2018

Revised 12 April 2019

Accepted 29 April 2019

Available online 21 May 2019

JEL classification:

L51

L71

Q35

Q53

Keywords:

Oil and gas regulation

Shale oil

Drilling

Firm exit

ABSTRACT

This analysis seeks to understand whether changes in oil regulation brought about by the shale revolution have restricted the pace of drilling and production. This hypothesis is tested using data on North Dakota and Montana both before and after North Dakota increased regulations that raise fixed costs. Results generally find that the new regulations had no statistical impact on the pace of drilling and production, however it is found that smaller operators reduced their production and exited. These results are instructive for policymakers who weigh the loss of economic welfare against improved environmental quality when deciding on new regulations.

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1. Introduction

Technical progress in hydraulic fracturing and horizontal drilling have helped spur a renaissance in U.S. energy production. Productivity improvements, when considered in isolation, may lead to greater economic growth and enhanced economic welfare. Demsetz (1967) argued that technological advance alters the net benefits of property right specification, generally so that property rights will be further specified to internalize new externalities that arise. The impact these newly specified property rights have on overall economic welfare will depend upon whether the regulated firms decide to forgo previously productive activities.

In the case of the shale revolution, there are numerous potential negative externalities associated with oil and gas production that can lead to changes in regulation. These include the possibility of polluting surface water and groundwater, degrading air quality, and spilling oil and waste (EPA, 2015; NETL, 2014). To mitigate the associated environmental externalities, many

[☆] We would like to thank Judd Boomhower, Will Duey, Harrison Fell, Ben Gilbert, Jonathan Hughes, Brett Jordan, Pete Maniloff and participants at the Midwest Economic Association conference, CESifo Energy and Climate Economics conference, University of Utah, University of Bristol, University of Wisconsin, the Front Range Energy Camp, the editor, and two anonymous referees for their comments and suggestions. Remaining errors are our own. Opinions expressed here are those of the authors. This paper is dedicated to Will Duey, who passed away in June of 2018, whose passion for sharing his knowledge of the oil and gas industry made all of those around him better off.

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state and local governments in the U.S. are considering or have implemented stricter regulations on oil and gas drilling and production operations. Proponents of stronger regulations consider them necessary to protect the environment. Opponents claim that regulations can be overly burdensome and hinder oil and gas extraction. Policymakers in several state governments are faced with balancing the often competing goals of resource development and environmental quality. Compounding the difficulty of this task is uncertainty over the extent to which tighter regulations on oil and gas operations ultimately reduce drilling and production.

This paper exploits a quasi-natural experiment to assesses the effects of stricter regulations on oil well drilling and production in North Dakota (ND) using regression discontinuity (RD) and difference-in-differences methodology. In 2012, ND tightened regulations that effectively increased the fixed cost of drilling for and producing oil. The regulation change, which is detailed in Section 2, included an increase in the well bonding requirements.¹ The boundary between ND and Montana (MT) divides several oil deposits, and many unconventional oil wells have been drilled near the border. MT did not implement the same regulations and serves as a control group in the analysis. While no control group is a perfect match to the treated group, we restrict the geographic area of study to a narrow window around the ND-MT boundary to ensure the treatment and control groups share many characteristics that influence drilling and production, such as geology, infrastructure, and geography. The outcomes analyzed here are drilling, production, and firm exit.

Valid estimation of an RD requires that the outcome is continuous around the treatment discontinuity point and that the discontinuity point is exogenously set. A number of different functional forms, both parametric and non-parametric, and bandwidths are used to ensure that any discontinuity in the outcome found at the ND-MT border is not due to misspecification of the data around the border. Given that the ND-MT border was set in 1863, when the U.S. acquired the Idaho Territories and set the end of the Dakota Territory at the 27th meridian west of Washington D.C., there is little concern that the border was set based on concerns for oil drilling. To further ensure that any discontinuity found at the ND-MT border is attributable to the regulation, this analysis utilizes data on drilling before the change in regulation for both ND and MT.

Results find no statistical change in the pace of drilling wells after the ND regulations came into effect. This result is consistent across multiple specifications, including different bandwidths and functional forms of the data. Production of oil did not on average decline with the imposition of the ND regulations, however the distribution of production amongst firms did change. Results consistently find reduced production from operators in the first quartile of production in the year previous to the regulation and increased production from operators in the fourth quartile.² The reduction in production for small operators in ND after the regulation went in effect, relative to production in MT, is about 0.5%. The reduction in production from small operators seems to be coming from operator exit. Regression and duration models show an increased propensity for small operators to leave the area of analysis while no statistical change is found for larger operators.

Taken together, these results imply that while the regulation had little, if any, impact on drilling and production, it did redistribute rents within the industry. In this light, the regulations look like larger operators were able to raise the costs of smaller competitors in order improve larger operators profitability, a la [Salop and Scheffman \(1983\)](#). With fewer small operators in the market for completion services (after drilling a well the operator hires a firm to “complete” the well by putting sand and other chemicals down the well to allow the oil to escape the rock), it is possible that the remaining operators have some oligopsonistic power when bargaining for completion services. Operators would use this power by offering to purchase less completions (in order to pay a lower price) and thus there would be an extended time period in between when drilling ends and production starts. A difference-in-difference analysis finds that wells in ND after the regulations went in place take three more weeks to start production after drilling has ended. A final component of the analysis estimates if the regulation had an effect on the occurrence of environmental incidents (e.g. oil spills). Data on incidents at the well level are only available for North Dakota, so an OLS regression with operator fixed effects and a time trend is performed, and the results suggest a relationship between the regulation change and fewer incidents.

The bulk of previous literature estimating the impact of regulation on industry behavior comes from the manufacturing industry. [Henderson \(1996\)](#), [Greenstone \(2002\)](#), [Walker \(2013\)](#), and [Becker and Henderson \(2000\)](#) all use air pollution policy to determine how the manufacturing industry altered its activity when environmental regulations increased. While manufacturing and oil drilling as industries have some similarities, there are important differences. Oil drilling has very mobile capital (rigs), which can move much quicker than a manufacturing plant, but the geology of a place is of paramount importance.³ [Ryan \(2012\)](#) looks at the impact of raising fixed costs in the cement industry and finds a large welfare loss to consumers through increased market power of incumbent producers. [Lade and Rudik \(2017\)](#) analyze the impact of gas flaring restrictions on the ND oil industry and speculate that the form of regulation may hinder small firms ability to stay in business.

The part of the literature most similar to the analysis undertaken here is [Boomhower, 2019](#), which examines the effects of well bond requirements implemented in Texas in 2002 on oil and gas production, firm exit, and environmental incidents. [Boomhower \(2019\)](#) uses a unique feature in the time dimension of the bonding requirement change while this analysis uses

¹ States require companies to submit bonds in order to cover the cost of environmental damage in the event the company is unable to pay. [Davis \(2015\)](#) provides an overview of the policy issues surrounding well bonding requirements and alternative regulatory approaches.

² Our measure of operator size is based on the production in the year previous to the policy. While financial measures of operator size would be preferred, they are not available for privately held companies. A cursory look at the names of companies in each size quartile gives the impression that our method is classifying operators correctly.

³ As [Maniloff and Manning \(2018\)](#) find, the optimal state severance tax is orders of magnitude above those currently observed. This reflects the relative importance of geology over regulatory decisions in the choice of where to drill.

the physical state border and a difference-in-difference set-up to estimate the impact of increased regulations. A principal difference of this paper is that it evaluates the effects of well bonding on new investment decisions (i.e. the drilling of new wells) for unconventional wells. Moreover, the wells drilled in Montana and North Dakota have a horizontal portion and are vertically deeper (~20,000 feet) than many of the conventional wells drilled in Texas (~3000 feet) and thus more expensive. Bonding an unconventional well thus makes up a smaller share of the total cost of a well relative to the conventional wells studied in Boomhower (2019), and the effects of higher fixed costs due to regulation may be limited in this case. On the other hand, oil producers had fewer onshore drilling options (other than Texas) in 2002 relative to the potential for ND drillers to move to MT in order to avoid the increased regulations. Many of the findings between the two papers are similar; a small impact on production that is concentrated in small firm's production losses and exits. We find a larger overall impact on exit (8% vs 6%) however Boomhower (2019) finds a larger probability of exit for small firms than we do (around 15% in the Texas example compared to 4% in ours).

Kim and Oliver (2017) look at changes to natural gas well regulations, including changes in well-bonding requirements, in Pennsylvania. They find that the increase in well bond requirements leads to a reduction in shale gas drilling. This result is counter to the results we find and those in Boomhower (2019), which is likely caused by fewer transportation options for gas (pipeline) relative to oil (pipeline, truck, rail) leading to more congestion possibilities in natural gas production. As a result of these transportation differences between oil and gas, it is likely that the results here would not transfer to shale gas plays.

As the results here are similar to that of other studies which show that geology and prices, less so taxes and other regulatory issues, are the main drivers of oil drilling decisions ((Boomhower, 2019; Kellogg et al., 2018; Brown et al., 2018)), the external validity of our analysis is not a strong concern. Additionally, the policies passed in ND dovetail similar policies that were passed across the US in light of the increased use of fracking to produce oil and gas (Zirotiannis et al., 2016). These results here are helpful to policymakers weighing the benefits and costs of further regulation in the oil and gas industry. It is quite common for industry associations to sponsor research that estimates the impacts regulation will have on the state or national economy. These estimates, by their nature, are prospective in that they predict how a proposed regulation will alter an industry and how that industry's change in behavior ripples through the economy. An analysis such as the one undertaken here provides a post-regulation evaluation of how the industry changed its behavior.

2. Background

This section provides a brief background on oil regulations and describes the 2012 rule changes in North Dakota. Essentially all of the wells drilled in the Bakken, the main formation that runs under the ND-MT border are to extract oil through fracking. The gas that maybe produced is generally associated gas, meaning the economics of the project is based purely on the oil. An unconventional or shale oil well generally has one additional step to the production process compared to conventional wells. Unlike conventional wells, drilling into rock does not immediately release the oil and/or gas in an unconventional well.⁴ Oil well operators hire a completion firm to "frack" the well. This is done by sending water, sand, and chemicals down the well to make small fractures in the rock and release the oil and/or gas. There are two important attributes of unconventional wells that make the investment in wells more certain. The first is that the use of manufacturing approaches in drilling make the costs more predictable as one moves from well to well. Accenture (2014) implies that the distribution of oil or gas volumes in a deposit (also known as the P10 and P90) are much tighter, meaning the firms have a better understanding of how much oil and/or gas will be produced. Second is that a larger share of the total production comes out in the first 12 months of an unconventional well compared to a conventional well (EIA, 2016). This makes it easier to lock in the price one will receive for the oil and/or gas. Putting these two together, the revenues to come from an unconventional well are more certain than in a conventional well.

Although all levels of government (federal, state, and local) have some role in regulating oil operations, state governments serve as primary regulators of drilling and production practices.⁵ In ND and MT, as well as many other states, a state agency sets regulations for all stages of well operations: drilling, production, and abandonment. Drilling regulations consist of well bonding requirements and rules on well spacing, disposal of drilling waste, cementing and casing standards, blowout protection, hydraulic fracturing procedures, and other activities. During the production stage, states regulate the venting and flaring of natural gas, handling and treatment of produced water, and reporting production volumes. Lastly, states set rules on shutting down well production, decommissioning equipment, and reclaiming sites.

On April 1, 2012, the North Dakota Industrial Commission (NDIC) adopted several revised rules on oil drilling practices. Although 26 different sections of the North Dakota Administrative Code were altered, there were four primary policy changes: higher well bond requirements, new restrictions on waste disposal, disclosure of chemicals used in hydraulic fracturing, and formal standards for hydraulic fracturing (NDIC, 2012b, 2016).

To bond a well, operators must submit a cash bond (e.g. a certificate of deposit) or a surety bond to the state regulatory agency prior to drilling. Upon reclamation of the drilling site, an operator can get the bond back. In practice, most wells are producing for a decade making the present value of the bond repayment negligible. In the case of surety bonds, a surety company issues a bond that the well operator submits to the regulator. If an environmental incident occurs or the well is abandoned, and the

⁴ Additionally, unconventional wells are drilled first vertically and then horizontally while a conventional well is only drilled vertically.

⁵ The federal government, for example, has certain authorities under the Clean Water Act and Clean Air Act to regulate water and air qualities. The power of local governments to implement rules on oil field practices is often limited and varies across states (Richardson et al., 2013).

operator cannot pay for the associated costs of cleanup or reclamation, the surety company is liable up to the face value of the bond. The 2012 regulation change in North Dakota increased the required face value for all new and existing wells from \$20,000 to \$50,000. In comparison, Montana requires a bond face value of \$10,000 for a single well that is deeper than 3500 feet (MBOGC, 2016), which is applicable to all Bakken wells in the state.

Raising bonding requirements has the effect of increasing the fixed cost of producing oil. Operators pay premiums to surety companies for issuance of the bond, and higher bond values increase premiums. The annual payments by operators to the surety company can be 1–5% of the bond's face value or up to 15–20% for relatively small firms (Gerard, 2000; Boomhower, 2019). Operators with relatively poor environmental histories or worse financial positions face higher premium costs (Davis, 2015), and these firms are likely to be impacted most by the higher bond requirements.

The second key component of the regulation change dealt with waste disposal. Drilling operations generate two primary types of waste: drill cuttings and mud. Drill cuttings are ground rock that result from creating the well-bore. Water or oil-based fluids, commonly referred to as mud, are used in drilling to remove cutting from the hole and prevent hydrocarbons in underground formations from rising to the surface and creating a “blowout”.

Following drilling operations, mud may be disposed of at the drill site in open pits, referred to as reserve pits or earthen pits. A report by the U.S. Fish and Wildlife Service states that these pits can contain diesel, oil, caustic soda, glycols, and potentially chromium, zinc, polypropylene, and lead, and may pose a risk to groundwater, surface water, and soils (Ramirez Jr, 2009). In the spring of 2011, flooding in North Dakota led to these pits overflowing and polluting nearby lands (MacPherson, 2012; Kusnetz, 2012). Birds and other wildlife may also be attracted to the pits, become entrapped, and killed (Ramirez Jr, 2009).

Prior to 2012, oil companies in North Dakota could dispose of mud waste in earthen pits or open receptacles. The 2012 regulation change revised rules so that, with limited exceptions, “no saltwater, drilling mud, crude oil, waste oil, or other waste shall be stored in earthen pits or open receptacles except in an emergency and upon approval by the director.”⁶ Operators thus have to store drilling mud and other liquids in tanks or dispose at other locations. In comparison, Montana regulations (Rule 36.22.1005) specify that waste must be disposed off-site for wells using brine or oil-based muds (MBOGC, 2016). While these disposal requirements seem like variable costs, they are largely fixed as they are paid before production starts and the additional cost of transporting and disposing of the waste, as opposed to open pits, is in arranging the transportation.

The revisions to the well bonding and waste disposal regulations were viewed as significant when enacted. The Assistant Director of the NDIC, the state's oil and gas regulatory agency, stated “These rule changes are the most significant changes we have made in the 31 years I've been with the Commission.” (NDIC, 2012a). In discussing the rule changes, the president of the North Dakota Petroleum Council⁷ stated “They are the most onerous regulatory changes we've ever seen,” and considered North Dakota's regulations “now overly burdensome and among the most stringent and costly in the nation.” (MacPherson, 2012). Taken together the well bonding requirements and disposal regulations were estimated to increase the cost of drilling a single well by up to \$400,000 (MacPherson, 2012). Given that a typical Bakken well is estimated to cost \$7–8 million, this represents up to 5–6% of total well costs.

The third major component of the regulation change required companies to disclose information on the chemicals used in fracking fluids through the FracFocus.org website. The fourth and final component of the rule change outlined requirements for the hydraulic fracturing process that were not previously addressed by the NDIC. These include such guidelines as testing the well casing before fracking and installing pressure relief valves. This analysis, however, cannot assess the effects of the changes to rules on fracking because Montana implemented similar changes around the same time. On August 27, 2011, about seven months before the effective date of the new North Dakota regulations, Montana adopted five new rules (MBOGC, 2011). Two of the new rules were relatively minor and dealt with notifying and submitting information to the state's regulator agency. The other three rules dealt with disclosure of chemicals used in frack fluids and the fracking procedures. As in North Dakota, companies were required to start reporting information on chemicals to the FracFocus.org website. The new fracking procedures were very similar to those passed North Dakota in requiring testing of well casing before fracking and installing relief valves.

In Montana and North Dakota, the Bureau of Land Management (BLM) manages oil and gas resources on public lands and Indian trust lands. The BLM manages, for example, oil and gas leases on the Dakota Prairie Grasslands in North Dakota and the Fort Peck Indian Reservation in Montana. Companies operating on lands managed by BLM must comply with federal regulations on drilling, production, and other areas of oil and gas development. Operators are still subject to state laws and regulations regarding oilfield practices, including well bonding requirements and waste disposal rules (NDIC, 2016; MBOGC, 2016). Moreover, the BLM well requires proof of a bond in the amount of \$10,000 per well and allows reserve pits for drilling waste. Thus, the change in North Dakota's regulations to increase bond requirements to \$50,000 per well and eliminate pits affected operations on BLM-managed lands as well.

3. Conceptual framework

The oil industry generally uses a net present value (NPV) calculation to determine which deposit to access by drilling a well. The [Society of Petroleum Engineers \(2011\)](#) defines the standard method for determining revenues and costs in the evalu-

⁶ The exceptions allowed include shallow wells with a total depth less than 5000 feet and temporary pits used in well completions, servicing, or plugging and to flare casing-head gas. All wells in the Bakken, and nearly every other formation, are deeper than 5000 feet.

⁷ This organization describes itself as “...the primary voice of the oil and gas industry in North Dakota since 1952.” (NDPC, 2012).

Table 1
Summary statistics of wells drilled within 20-and 30-mile windows.

	Well		Well Distance from MT-ND Border					
	Count	Mean	Std. Dev.	Min	P25	P50	P75	Max
20-Mile Window								
April 2010–March 2012								
Montana	156	7.8	5.42	0.02	3.35	6.86	12.29	19.79
North Dakota	332	10.52	5.62	0.09	5.83	10.29	15.76	19.96
April 2012–March 2014								
Montana	158	7.83	5.08	0.1	3.56	7.14	11.1	19.82
North Dakota	425	12.43	5.54	0.12	9.12	13.45	17.04	19.99
30-Mile Window								
April 2010–March 2012								
Montana	180	10.13	7.86	0.02	4.17	8.04	15.02	29.79
North Dakota	578	16.78	8.64	0.09	8.84	17.39	24.43	29.97
April 2012–March 2014								
Montana	212	12.37	8.99	0.1	5.24	9.18	21.25	29.61
North Dakota	883	19.12	7.78	0.12	13.85	20.33	25.53	30

The windows include wells drilled in Montana and North Dakota that are within 20/30 miles of their shared border.

ation of a drilling project. Projects whose return is higher than the minimum acceptable rate of return are generally undertaken.⁸ A well will have an expected production, and firms hedge or have an expectation of what the price of oil will be when the well is producing. The cost of drilling, completing or fracking the well and other costs that are used to calculate the NPV of the project. The new regulations outlined in Section 2 will raise the operating costs of a project in ND. This lowers the NPV of a given project, relative to before the regulation changes. Firms can move drilling to MT where these operating costs have not changed, thus the NPV of wells drilled and economic welfare may be unchanged. Alternatively, these increased operating expenses could lower the rate of return of a project below that of the minimum acceptable rate of return, and if no such projects exist in MT, it will cause a project to be abandoned. A final option is if the increased operating expenses lowers that project's rate of return but the return is still above the minimum acceptable rate of return, the project will still be undertaken but the operator either earns less of a profit or it bargains with its input suppliers to reduce costs elsewhere so that the operator's profits remain constant. This would not change output but shift the distribution of rents. One manner in which operators can alter their input costs is through the payments made to landowners for access rights to subsurface resources. These leases are generally private but a selection of Texas gas leases were made publicly available and analyzed by Timmins and Vissing (2014). They find that the average length of a lease is 40 months, implying that operators can't immediately alter their payments landowners. Another manner in which rents can be redistributed is discussed in Davis (2015) and Boomhower (2019). Bonding costs can disproportionately affect small operators as they are more likely to be credit-constrained. In this case, an increase in bonding requirements might imply that it is more likely that a project becomes unprofitable for a small operator than for a large operator. From this framework, hypotheses around changes in production and drilling are formed.

4. Data

Data on well location (latitude and longitude) and the drilling date are available from Drillinginfo (2015), which is a subscription-based source of oil and gas statistics and information. Table 1 summarizes the number of oil wells drilled within two windows (20 miles and 30 miles) around the MT-ND border and their distances from the boundary. The RD approach uses 20-and 30-mile windows on each side of the MT-ND boundary, however, additional results are provided in Appendix A. In the 2-year period prior to the regulation change (April 2010–March 2012), 156 wells were drilled in Montana within 20 miles of its eastern border with North Dakota with the closest well being just 100 feet from the boundary. In the 20-mile window on the North Dakota side, 332 wells were drilled over the same time period with one well as close as 500 feet from Montana. In the two year period following the regulation change (April 2012–March 2014), 158 and 425 wells were drilled in the Montana and North Dakota 20-mile windows, respectively.⁹ For reference, over the time period of our sample there were around 4700 oil wells drilled in North Dakota, implying that the 30 mile window contains around 30% (1400 of 4700) of the wells drilled in North Dakota. This helps ensure that our results are externally valid as we are analyzing a relatively large share of the wells drilled in ND.

⁸ Kellogg (2014) models the decision of when to drill a conventional well and we follow that framework. Kellogg (2014)'s model provides a framework to understand how uncertainty affects drilling. As this analysis is comparing whether to drill just in ND or just in MT, we abstract from uncertainty as it is the same for both decisions and uncertainty is significantly smaller for unconventional wells.

⁹ The fact that there are similar numbers of wells drilled before and after the treatment helps ensure that the results of later analyses on production and firm exit are not driven by well vintages or other events that may skew interpretations of the results.

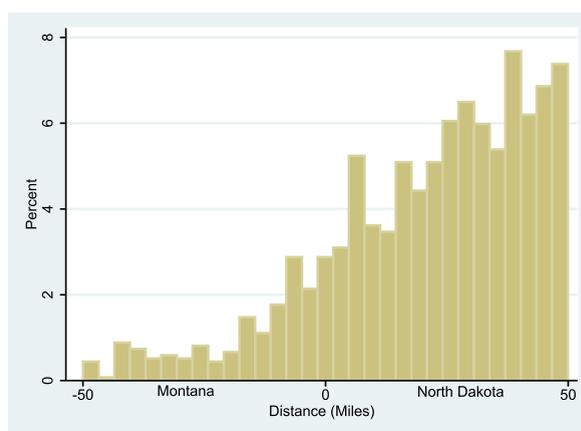


Fig. 1. Histogram of wells drilled near ND-MT border (April 2010–March 2012).

Table 2
Oil production summary statistics.

	Oil Production (Barrels per Day)			
	2010	2011	2012	2013
Montana				
Quartile 1	295	244	304	246
Quartile 2	723	880	1103	1544
Quartile 3	2183	2844	4726	6149
Quartile 4	6085	9305	12,072	12,909
Total	9286	13,273	18,205	20,847
North Dakota				
Quartile 1	57	70	72	38
Quartile 2	369	754	758	4320
Quartile 3	1749	4305	8666	9747
Quartile 4	29,655	31,742	33,264	28,465
Total	31,830	36,871	42,760	42,571

Oil production is the average number of barrels produced per day within 10 miles of MT-ND border for all companies in a quartile. Quartiles are constructed based each operator's total oil production in MT and ND in 2011, so the number of operators within a quartile may not be the same in both states. Production data shown are only for operators that were active in the year 2011 and included in the analysis.

Fig. 1 presents a histogram of wells drilled within fifty miles of the ND-MT border in the 2 years leading up to the regulation enactment (April 2010–March 2012). There is no obvious discontinuity in the density of drilling activity at the border before the regulation change. This figure also shows that drilling becomes more prevalent in North Dakota as distance from the border increases. This is largely explained by the existence of a fold in the subsurface rock formations called the “Nesson Anticline” that creates a so called “sweet spot” because natural fractures in the rock enhance oil production. The flexible functional forms used in an RD design will allow for drilling to vary nonlinearly in distance from the cutoff.

Table 2 presents summary statistics for oil production near the Montana and North Dakota boundary from 2010 to 2013. The table shows the average daily production (barrels per day) in each state within 10 miles of the border. Production is broken down by company size, where quartile 1 (Qrt 1) refers to the smallest firms and quartile 4 contains the largest firms. Operators are partitioned into quartiles based on their size, which is measured as total oil production in 2011 (prior to the regulation change). Oil production varies greatly across firms, with some of the smallest firms having less than 10 barrels per day and the larger operators producing 3000 barrels or more a day.

5. Empirical strategy

This paper employs two empirical strategies. The RD design used to evaluate the effect of the regulations on drilling activity is described in Sections 5.1 and 5.2. Sections 5.3 and 5.4 discuss a difference-in-differences approach to assess the effects on operator oil production and exit. Both of these strategies restrict observations to those near the border in order to limit the impact of time varying unobservables. This is achieved by ensuring that the time invariant unobservables are relatively similar

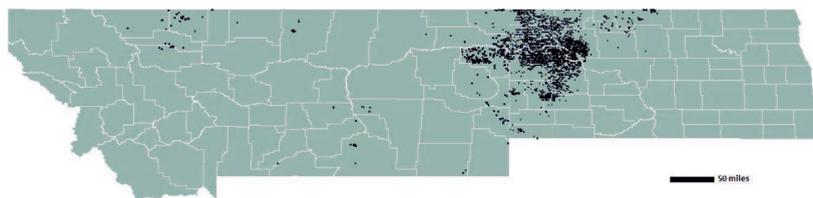


Fig. 2. Oil wells drilled in Montana and North Dakota (April 2012–October 2015).

and thus changes in the industry, such as the productivity of propellants used in fracking or increased amount of housing services for oil company employees, are unlikely to differentially impact the two areas.¹⁰

5.1. Drilling activity

An RD design is well suited to evaluate the effects of the regulation change on drilling activity for three reasons.¹¹ First, the border between Montana and North Dakota intersects several hydrocarbon-bearing rock layers (i.e. geologic formations), such as the Bakken, Three Forks, Madison, Red River, and others (NDGS, n.d.). This creates a cutoff that is necessary in a sharp RD, where observations on only one side of the threshold receive the treatment. Second, an area's hydrocarbon potential is a function of the geologic characteristics of the underlying oil or gas reservoirs. "Location, location, location" are sometimes said to be the three factors that make a "good well" because geology has such influence on oil and gas production potential (Gold, 2015; Hume, 2015). Thus, wells drilled near one another, but on other sides of the border, may be similar in their oil production and economic attractiveness. Third, an RD can flexibly model drilling activity over space. Fig. 2 shows there are substantially more wells drilled in North Dakota (4815 wells from April 2012–October 2015) than Montana (498 wells). Drilling in North Dakota is concentrated about 50–75 miles away from the border with Montana due to the Nesson Anticline discussed above. The RD analysis focuses on a narrow window around the border (20–30 miles on each side) to prevent the relatively oil-rich areas of North Dakota from influencing the results, but RD estimation with various windows are presented in Appendix A.

The units of observation are geographically-defined cells near the MT-ND border. The cells are identical in size, equal in length and width, and each cell is located in either Montana or North Dakota. The nearly straight line that creates the Montana–North Dakota boundary, as well as the border with Canada (the 49th parallel north), make constructing the cells straightforward. Wells in the Bakken were initially spaced so that one well occupied a square mile (referred to as 640-acre spacing), but have become closer so that spacing typically range from 40-acre to 160-acre (4–16 wells per square mile). Cell dimensions of 1 × 1 mile are thus a natural starting point, although robustness checks are performed where the cell dimensions are modified to 5 × 5 miles.

Equation (1) presents a regression model for a parametric RD design.

$$\ln \text{Wells}_i = \alpha + \beta D_i + f(x_i) + \gamma_i + \epsilon_i \quad (1)$$

The variable $\ln \text{Wells}_i$ is the natural log of the number of wells drilled in cell i before or after the regulation change, where each cell is a one-square-mile block of land. The sample period is limited to wells drilled from April 2010 to March 2014 split in half by the date of the change in regulation, and robustness checks show that varying the start or end of the sample period does not influence the results (Table 21 of Appendix A).¹²

The assignment variable (D_i) is equal to one for cells in ND and zero for cells in MT. The force variable (x_i) is the distance from the border to the midpoint of cell i , and the distances for MT cells are negative. The polynomial function $f(x_i)$ maps the relationship of distance from the border to drilling in a flexible manner. The function is defined as follows: $f(x_i) = f_L(x_i) + D_i(f_R(x_i) - f_L(x_i))$, where $f_L(x_i)$ is a polynomial function of x for the left side of the cutoff (MT) and $f_R(x_i)$ is polynomial function for the right side (ND).

The force variable measures only a cell's east-west distance from the border, and thus capture one dimension of spatial variation in drilling. The term γ_i is a latitude fixed effect included to account for north-south variation in drilling activity.¹³ Lastly, the error term is denoted by ϵ_i .

¹⁰ If one runs the an analysis of drilling activity in all of ND and MT around the time of the ND regulations, the results show a statistically significant increase in wells drilled in ND after the regulations went into effect relative to MT. Rather than interpret this result as increasing regulation leading to more well drilling, we would argue that increases in well productivity over time led to more wells being drilled near the Nesson Anticline, the "sweet spot" of the Bakken. This result furthers our belief that limiting the distance around the border is the prudent way to analyze these regulations.

¹¹ This is similar to the approach taken by Cust and Harding (2014), who exploit country boundaries to evaluate the effects of institutions on oil exploration.

¹² North Dakota revised oil and gas regulations on spill reporting, pipelines, and waste treatment plants in April 2014. April 2012–March 2014 thus serves as a natural post-treatment time period.

¹³ This is accomplished in the estimation by including dummy variables for cell distance from the intersection of the MT-ND border with Canada (i.e. its north-south distance). Note that this is feasible because by construction, each cell's distance from the Canadian border is discrete. Results without this latitude fixed effect are presented in Table 22. Including this term does not have an effect on the overall results.

Estimation of Equation (1) may not identify effects of the regulation change if there is a pre-existing discontinuity in drilling at the MT-ND border. This may arise from several factors, such as differences in oil severance tax rates, state corporate income tax rates, or other regulatory requirements. Hence it is necessary to estimate the how the discontinuity at the border changes following the stricter regulations.

In equation (2), the pre-and post-treatment sample periods are pooled to estimate the difference in the discontinuity before and after the revision to the regulations. This is similar to the “pretest RD” method introduced by [Wing and Cook \(2013\)](#) (See [Appendix B](#)). The pretest RD improves identification of the standard RD design by including pre-treatment observations, which contain information on the underlying relationship between the force variable and outcome variable. In this paper, not only do pre-treatment observations help establish the relationship between distance from the border and drilling activity, but they are also necessary to account for a potential pre-existing discontinuity at the border.

$$\ln Wells_{it} = \rho D_{it} + \zeta S_i + h_0(x_i) + T_{it}(h_1(x_i) - h_0(x_i)) + \gamma_i + \epsilon_{it} \quad (2)$$

where $h_0(x_i) = h_{0L}(x_i) + S_i(h_{0R}(x_i) - h_{0L}(x_i))$,

and $h_1(x_i) = h_{1L}(x_i) + S_i(h_{1R}(x_i) - h_{1L}(x_i))$

The dependent variable ($\ln Wells_{it}$) is the natural log of the number of wells drilled in cell i in period t . There are two periods: $t = 0$ is the pre-treatment period (April 2010–March 2012) and $t = 1$ is the post-treatment period (April 2012–March 2014). Note that Tables 20 and 21 of [Appendix A](#) show that varying the sample period does not alter conclusions drawn from the results. The variable S_i indicates whether the cell is in North Dakota ($S_i = 1$) or Montana ($S_i = 0$). The polynomial functions allow drilling activity to vary across time periods (pre-and post-treatment) and the cutoff. The functions $h_0(x_i)$ and $h_1(x_i)$ are polynomials for the pre-treatment and post-treatment periods, respectively. The variable T_t is equal to zero for cells in the pre-treatment ($T_0 = 0$) period and equal one for cells in the post-treatment ($T_1 = 1$) period. For example, for $t = 0$, drilling activity follows the polynomial $h_0(x_i)$, which in turn differs for the Montana side ($h_{0L}(x_i)$) and North Dakota side ($h_{0R}(x_i)$). The term γ_i is the fixed effect for the north-south position of cell i , and ϵ_{it} is the error term.

A parametric RD is applied, as opposed to a nonparametric RD, because the force variable is discrete. Distance is measured from the border to the midpoint of each cell (0.5, 1.5, 2.5 miles, etc.). [Lee and Card \(2008\)](#) note that the non-parametric and semi-parametric RD methods rely on comparing outcomes in arbitrary small neighborhoods around the threshold. In cases with discrete force variables, it is not possible to be arbitrarily close to the threshold even as the sample size grows. The approach recommended by [Lee and Card \(2008\)](#), which is followed in this analysis, is to use parametric functional form and cluster the standard errors on the force variable. Non-parametric RD yields similar results though (Table 19 of [Appendix A](#)).

The polynomial order is selected based on the specification’s Akaike information criterion (AIC) value. Based on the findings by [Gelman and Imbens \(2014\)](#), who caution against using high order polynomials, only models with zero through second-order polynomials are considered. In choosing the width of the window around the border, there is a trade-off between observations and potential bias. Results for 20-mile and 30-mile windows are presented in Section 6, but results for additional windows in [Appendix A](#) give similar findings.

5.2. RD design identification

This section discusses six issues that threaten identification through the RD design. First, a necessary assumption is that the conditional regression functions are continuous at the cutoff. That is, there is no discontinuity in the outcome variable at the cutoff— that is unrelated to the treatment. As discussed in Section 5.1, this assumption may be violated because of pre-existing differences between Montana and North Dakota. This is resolved by pooling pre-treatment and post-treatment data into a single RD (Equation (2)) and estimating the difference in this discontinuity following the regulation revisions.

The second identification issue is whether there is a discontinuity in the density of the force variable near the cutoff. In this paper, the unit of observation is a geographically-defined cell, and firm decisions on where to drill are the outcomes of interest. Thus, if drilling is relatively sparse on the North Dakota side following the regulation change, this would not necessarily imply that the identification strategy is invalid but rather that the new regulations has an effect. [Fig. 3](#) in Section 3 shows there is no apparent discontinuity in the density of drilling activity at the boundary (i.e. firms don’t avoid the places near the border) in the two years leading up to the regulation change (April 2010–March 2012).

Third, identifying the treatment effect requires the stable unit treatment value assumption (SUTVA) to hold. The Montana observations must not be affected by the treatment applied to North Dakota. This assumption is violated if stricter regulations in North Dakota cause firms to relocate to Montana, which would cause drilling activity in Montana to be higher than it would be otherwise. Since the validity of this assumption is unknown here, we consider the estimation results to be an upper bound of the average treatment effect at the threshold.

Fourth, the enactment of regulation revisions may coincide with temporal shifts in drilling from one state to the other. A possible scenario is that drilling was concentrated in one state in the years leading up to the regulation change; that state became saturated with wells near the time of regulation change, and activity then shifted to other state. Such a situation may incorrectly attribute the shift in drilling to the regulations. To deal with this issue, a control variable for the number of previously drilled wells within a cell is added to equation (1). The number of wells previously drilled is specified in both linear and quadratic

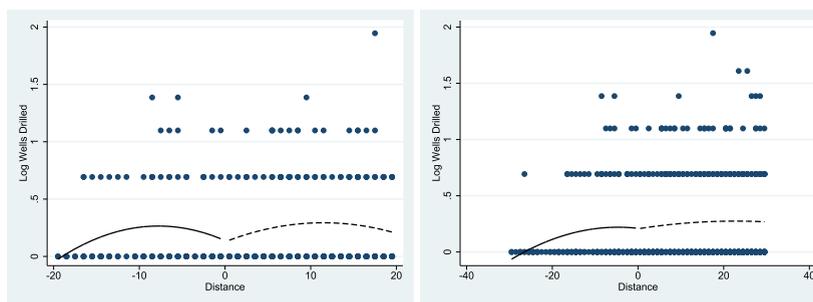


Fig. 3. Drilling activity at MT-ND border pre-treatment (Apr. 2010–Mar 2012). This figure shows drilling activity for a 20 mile window (left) and 30 mile window (right) either side of the MT-ND border during the pre-treatment period (April 2010–March 2012). Positive distances from the border indicate ND and negative in MT.

forms, which allows for drilling within a cell to become saturated and decline over time. There is no meaningful difference in the estimation results (Table 24 of Appendix A) when including this control.

Fifth, one might be concerned with a state border as the discontinuity because of sorting by oil firms. Indeed, Lee and Card (2008) urge caution in using state borders as a cutoff as differences in outcomes could be due to unobservable sorting by entities as opposed to the treatment envisioned by the researcher. We feel these concerns are not warranted in this example for a couple of reasons. First, we use a difference-in-difference framework to control for any time invariant unobservables that might lead to sorting. Second, oil exploration companies have to work where the deposits are, thus it is common for them to work in multiple states.¹⁴ Third, both MT and ND had little oil drilling activity until the advent of hydraulic fracturing, thus it is unlikely that an oil firm would have specialized in one state. Finally, the geology around the border would be similar given the small distances we are analyzing, making it even less likely for firms to sort on one side of the border.

Sixth and finally, a common identification issue with applications of RD is endogeneity of the cutoff's placement. It is highly unlikely that oil deposits had any influence over location of the Montana-North Dakota border, and furthermore that such placement would be correlated with the 2012 regulation change. The current Montana-North Dakota border was originally the eastern border of the Idaho territory created by Congress in 1863 (State Historical Society of North Dakota, 2016). This later became the border between Montana and North Dakota, when the two states were formed in 1889. The first oil wells were drilled in Montana and North Dakota in 1901 and 1929, respectively (Erdmann, n.d.; NDGS, n.d.). Moreover, the border is reported to have been chosen "out of the blue", and "The line does not coincide with any particular section or half-section line, or anything else of local or regional significance." (Bluemle, 2007).

5.3. Oil production and exit

A difference-in-difference approach is used to determine the effects of the more stringent regulations on operator oil production and exit. Higher regulatory requirements may increase the fixed cost of oil production and cause firms to stop drilling, which would lead to reductions in production. For example, operators might decide not to re-frack wells or drill fewer wells, which would subsequently decrease production. The stricter drilling waste disposal rules are not expected to affect production at existing wells, but these rules can reduce production by discouraging the drilling of new wells.

Equation (3) estimates the effects of the revised regulations on operator-level oil production.

$$\text{LnProd}_{ijt} = \tau D_{jt} + \theta_i + \kappa_j + \lambda_t + \eta_{ijt} \quad (3)$$

The dependent variable (LnProd_{ijt}) is the natural log of oil produced by operator i in state j during month t . The quantities of oil produced are limited to an operator's production from wells within 10 miles of the MT-ND boundary, which ensures the treatment and control groups are similar. The treatment variable (D_{jt}) is equal to one for observations in North Dakota after the regulation change (April 2012 and onward) and zero otherwise. Time-invariant unobservables are controlled for with fixed effects for the operator (θ_i), state (κ_j) and month (λ_t). The last term (η_{ijt}) is the idiosyncratic error. If operator i stops producing, they are dropped from the sample.¹⁵

The final regression model is shown in Equation (4), which estimates the effect on operator exit from the 10-mile window in North Dakota.¹⁶

$$\text{Exit}_{ijt} = \mu D_{jt} + \phi_i + \psi_j + \omega_t + v_{ijt} \quad (4)$$

¹⁴ A look at the operator names on each side of the border reveal that there are around 140 operators in ND and 125 in MT with 36 operators with wells in both during our sample. Given that operators may own subsidiary companies that are difficult to link to the parent operator, these numbers should be taken with a grain of salt. The larger point being that there are many operators in each state and some work in both states.

¹⁵ Keeping these zero production firms in the data does not change the interpretation of the results. First (smallest) quartile firms see the largest decrease and fourth quartile (largest) see an increase, however the sum of increases and decreases across quartiles is not statistically different than zero.

¹⁶ A duration analysis performed in Appendix C provides similar findings.

The dependent variable ($Exit_{ijt}$) is equal to one if operator i exits the study area of State j in month t ; and zero otherwise. Note that this measures only if an operator exits the area within the 10 miles of the border and not whether it ceases operations in the entire state. An exit occurs in the month in which an operator's production falls to zero and remains zero throughout the sample period. The treatment variable (D_{jt}) is equal to one for observations in North Dakota after the regulation change (April 2012 and onward) and zero otherwise. Fixed effects are included to account for time-invariant effects specific to the operator (ϕ_i), state (ψ_j), and month of production (ω_t). The last term, v_{ijt} , is the idiosyncratic error.

Equations (3) and (4) estimate the average effect across all operators, but firms may respond differently depending on their size. Section 6.2 provides estimation results where the coefficient estimate for the treatment variable is allowed to differ by firm size. Each operator's total oil production in all of Montana and North Dakota in 2011 (prior to the regulation change) is the proxy used for firm size.

It is usually more costly for smaller firms to meet well bond and other fixed cost regulation requirements. Our best expectation is that a firm exits by either selling wells or permanently shutting in a well.¹⁷ Operators, especially small companies, often post a surety bond. As discussed in Section 2, in this situation, a surety company issues a bond to the operator, who then submits the bond to the state regulator. The operator pays the surety company a premium, which is typically a percentage of the face value of the bond. Firms with relatively limited assets, with poor environmental or safety records, or in precarious financial positions, often pay higher premiums. Smaller firms may pay higher premiums to surety companies because these operators are potentially judgment proof, which occurs when a firm is unable to pay its full legal liabilities. For example, in bankruptcy, a company is liable up to only the value of its assets and can have the obligations that exceed this amount dissolved. Bonding requirements could require operators to invest in safety and set output at levels that are socially optimal if operator behavior was perfectly observable by surety companies. Surety companies recognize that because operator behavior is not perfectly observable, smaller firms have less of an incentive to undertake safety measures and avoid risk because they will not be fully liable for potential damages. Thus, these operators face higher premiums, and increasing the well bonding requirement has a larger financial impact on smaller (and potentially judgment proof) firms than larger firms.

5.4. Difference-in-difference identification

There are three primary identification issues to address with the estimation equations (3) and (4). First, there is the potential for policy endogeneity. That is, there may be unobserved factors that influence production (or firm exit) and North Dakota's adoption of the revised regulations. Inclusion of the state fixed effect controls for time-invariant unobservables specific to each state. These unobservables may be differences across the two states in existing tax structures, general friendliness to resource development, or geographic features within the window. Time-varying, state-level unobservables, however, are not accounted for with a state fixed effect. One potential time-varying factor is that the breakthroughs in horizontal drilling and hydraulic fracturing may have had different effects on oil activity in Montana and North Dakota. North Dakota encompasses more of the Bakken and the so called "sweet spots" that offer higher oil production rates. As the Bakken boom was occurring, it is conceivable that policy-makers in North Dakota judged that passing stricter regulations would have a limited effect on oil activity because evolving technology would unlock the state's rich hydrocarbon potential. To deal with this issue, the sample is restricted to oil production and exit in each state that is within 10 miles of the MT-ND border. This ensures that the resource potential is very similar across the treatment and control groups and the regulation change should not be endogenous in the models.

The second identification issue is the appropriateness of the control group. To accurately estimate the treatment effect, the control group must serve as an appropriate counterfactual to North Dakota. Including oil production from only wells within a 10-mile window on each side of the border allows for wells in the sample to share similar geology and production potential. Fig. 3 depicts Montana and North Dakota oil production within the 10-mile window and shows that pre-treatment, production in the two states generally moves in step. Formal tests show no difference in pre-treatment trends between the two states (Table 6).

Third and finally, as discussed in Section 5.2, the SUTVA is required to identify the average treatment effect. The control group may be contaminated if firms shift production activities to Montana in response to the regulation change. This is an issue in many studies that attempt to estimate the effects of environmental regulations on firm investment decisions (Millimet et al., 2009). Thus, as in the RD design, the difference-in-difference estimation results can be interpreted as an upper bound of the treatment effect.

6. Results

6.1. RD results

Fig. 3 shows well drilling near the MT-ND border in the two-year period prior to the regulation change (April 2010–March 2012). The log number of wells drilled within a cell is on the vertical axis, and the cell's distance from the border is shown

¹⁷ Unfortunately there is no publicly available dataset on well sales that we are familiar with to test which of these options firms are undertaking. Since unconventional wells have a quick decline curve (a majority of the production happens within the first 12 months) it seems unlikely firms would temporarily shut in a well in hopes of higher prices in the future.

Table 3

RD results for well drilling pre-treatment (Apr, 2010–Mar 2012).

	20-Mile Window			30-Mile Window		
	(1) LnWells	(2) LnWells	(3) LnWells	(4) LnWells	(5) LnWells	(6) LnWells
D_i	0.052 (0.041)	0.015 (0.120)	−0.033 (0.154)	0.088** (0.034)	0.020 (0.085)	0.024 (0.123)
Poly. Order	Zero	1st	2nd	Zero	1st	2nd
AIC	330.0	251.5	248.1	526.0	470.3	468.2
R^2	0.004	0.353	0.355	0.010	0.274	0.274
Clusters	40	40	40	60	60	60
N	354	354	354	546	546	546

The dependent variable is the number of wells drilled. Standard errors clustered on force variable (x_i) in parentheses. Specification with lowest AIC is preferred. Zero polynomial order models do not include the latitude fixed effect term γ_i . Estimation results for equation (1). D_i is 1 for ND and zero for MT. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

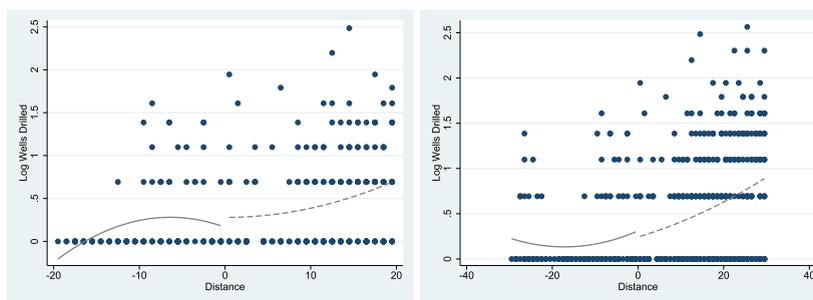


Fig. 4. Drilling activity at MT-ND border post-treatment (Apr, 2012–Mar 2014). This figure shows drilling activity for a 20 mile window (left) and 30 mile window (right) either side of the MT-ND border during the post-treatment period (April 2012–March 2014). Positive distances from the border indicate ND and negative in MT.

on the horizontal axis.¹⁸ The cutoff is at distance zero with Montana on the left side and North Dakota to the right. The left panel of Fig. 3 captures a 20-mile window on each side of the border with a fitted quadratic. Estimation of equation (1) with the function $f(x_i)$ as a second-order polynomial yields the lowest AIC score for all models with zero to second-degree polynomials. The right panel presents a 30-mile window with a quadratic polynomial (selected by lowest AIC value). Fig. 3 suggests there is not a discontinuity in drilling activity at the border prior to the regulation change, and this is confirmed in Table 3.

Table 3 presents the estimation results of Equation (1) for well drilling during the two-year period prior to the regulation change. Results for a 20-mile window with zero, first, and second-order polynomials are shown in columns 1–3. The coefficient estimates for the assignment variable (D_i) are not statistically indistinguishable from zero at any reasonable level across the different specifications. For a 30-mile window (columns 4–6), the estimate of the coefficient for the assignment variable is statistically significant at the 5% level in only the zero-order polynomial model. The specification with a quadratic polynomial is preferred (based on lowest AIC value) for both the 20-mile and 30-mile windows. Table 15 of Appendix A shows the coefficient estimate for several windows (10, 20, 30, 50, 75, and 100 miles) and polynomial of orders zero through six.

Fig. 4 displays drilling activity in the two years following the regulation change (April 2012–March 2014). Twenty and thirty mile windows are shown in the left and right panels, respectively, with fitted second-order polynomials, which are selected based on AIC values. Small, statistically insignificant discontinuities at the MT-ND border are apparent in both panels.

Table 4 provides the estimation results of Equation (1) for well drilling after the regulation change (April 2012–March 2014). Overall, there is little evidence of a discontinuity in drilling activity at the border. The coefficient estimates for the assignment variable (D_i) are positive and statistically significantly different from zero at the 1% level in only the models with a polynomial of order zero (columns 1 and 4). In the specifications with a second-order polynomial, the coefficient estimates for the assignment variable are not statistically indistinguishable from zero (columns three and six).

¹⁸ A large number of cells have one well drilled which leads to a zero in the figure, due to the log of one being zero. The results from our analyses are consistent when we use a count model as in Table 13 and 14.

Table 4
RD results for well drilling post-treatment (Apr, 2012–Mar 2014).

	20-Mile Window			30-Mile Window		
	(1) LnWells	(2) LnWells	(3) LnWells	(4) LnWells	(5) LnWells	(6) LnWells
D_i	0.275*** (0.073)	-0.138 (0.202)	0.025 (0.309)	0.396*** (0.061)	-0.063 (0.146)	-0.097 (0.238)
Poly. Order	Zero	1st	2nd	Zero	1st	2nd
AIC	517.7	462.1	460.2	961.0	823.8	820.7
R^2	0.061	0.359	0.362	0.088	0.422	0.425
Clusters	40	40	40	60	60	60
N	340	340	340	550	550	550

The dependent variable is the number of wells drilled. Standard errors clustered on force variable (x_i) in parentheses. Specification with lowest AIC is preferred. Zero polynomial order models do not include the latitude fixed effect term γ_i . Estimation results for equation (1). D_i is 1 for ND and zero for MT. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

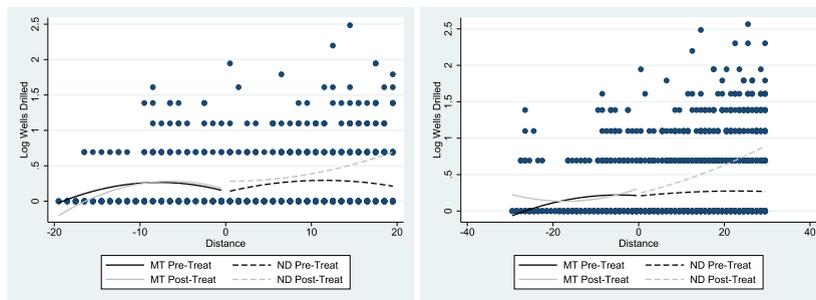


Fig. 5. Drilling activity at MT-ND border pre-and post-treatment (Apr, 2010–Mar 2014). This figure shows drilling activity for a 20 mile window (left) and 30 mile window (right) either side of the MT-ND border during both the pre- and post-treatment period (April 2010–March 2014). Positive distances from the border indicate ND and negative in MT.

Fig. 5 contains wells drilled in both the pre-treatment period (April 2010–March 2012) and post-treatment period (April 2012–March 2014) for twenty and thirty mile windows. The fitted polynomials are allowed to vary across the threshold and time (pre-and post-treatment periods). The difference at the cutoff (distance zero) between the fitted curves labeled “MT Pre-Treat” and “ND Pre-Treat” depict the discontinuity existing prior to the regulation change. The discontinuity following the regulation change is shown by the difference in the curves labeled “MT Post-Treat” and “ND Post-Treat”. The estimated effect is measured by the change in the discontinuity following the regulation revisions. Table 5, which presents the estimation results for Equation (2), shows there is little evidence of a shift in the discontinuity. For both the 20-mile and 30-mile windows, the coefficient estimate for the treatment variable (D_{it}) is not statistically significant in the specifications with a first-order and second-order polynomial, the latter of which has the lowest AIC value. The 95% confidence interval has a low value of almost 1% reduction in drilling, implying that the impact of the regulations would have to be that large in order for our model to find a statistically significant result.

Robustness checks, found in Appendix A, that vary the window widths and polynomial orders, among other things, offer no evidence that the regulation change had an effect on drilling activity. Using a Poisson count model instead of the log of wells has no impact on the interpretation of the results, see Appendix A, Table 13 and 14. A final robustness check is to estimate a difference-in-difference model across different distances around the border. This can be found in Appendix A, Table 25. The

Table 5
RD results for well drilling (Apr, 2010–Mar 2014).

	20-Mile Window			30-Mile Window		
	(1) LnWells	(2) LnWells	(3) LnWells	(4) LnWells	(5) LnWells	(6) LnWells
Treatment D_{it}	0.223*** (0.073)	-0.098 (0.182)	0.035 (0.282)	0.308*** (0.060)	-0.020 (0.137)	-0.151 (0.206)
Poly. Order	Zero	1st	2nd	Zero	1st	2nd
AIC	877.6	759.2	756.4	1569.0	1368.7	1366.3
R^2	0.060	0.285	0.288	0.113	0.332	0.334
Clusters	40	40	40	60	60	60
N	694	694	694	1096	1096	1096

The dependent variable is the number of wells drilled. Standard errors clustered on force variable (x_i) in parentheses. Specification with lowest AIC is preferred. Zero polynomial order models do not include the latitude fixed effect term γ_i . Estimation results for equation (2). Treatment D_{it} is 1 for ND for months after April 2012 and zero for MT and ND before April 2012. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

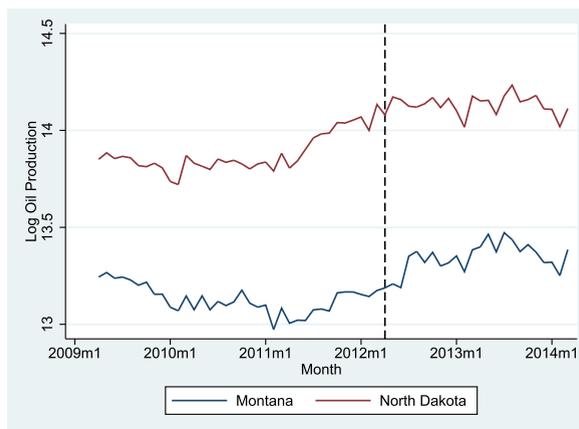


Fig. 6. Oil Production within 10-mile window of MT-ND Border (Apr, 2009–Mar 2014). This figure shows oil production within 10 miles of the MT-ND border each month between April 2009 and March 2014. This figure reveals that the pattern of oil production on each side of the border was generally trending in the same direction.

Table 6

Oil production pre-treatment trends (Apr, 2011–Mar 2012).

	(1) LnProd	(2) LnProd
<i>Time</i>	0.02* (0.01)	2.31 (3.27)
<i>ND × Time</i>	0.03 (0.02)	−0.37 (6.68)
<i>Time</i> ²		−0.00 (0.00)
<i>ND × Time</i> ²		0.00 (0.01)
Operator FE	Yes	Yes
<i>N</i>	942	942
<i>R</i> ²	0.045	0.045

The dependent variable is the natural log of oil production. Standard errors clustered on operator in parentheses. This analysis tests whether ND oil production trended differently than MT in the period leading up to the change in regulation. Column 1 tests for a change in linear trend while column 2 tests for a change in the quadratic trend.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

results mimic what is seen in Fig. 5. At smaller distances around the border, there is no change in drilling activity. At larger distances, there is an increase in drilling in ND.

One may be concerned that the results shown thus far do not account for the fact that landowner leases are not completely flexible and this is the cause for the null results related to drilling activity. As discussed in Timmins and Vissing (2014), landowner leases are generally about 40 months long. Table 20 re-runs Equation (2) but removes the year immediately before and after the regulation was implemented to determine whether previous results are influenced by the inability to terminate or change lease terms. Results generally find no statistical change in drilling activity when comparing discontinuous time periods that allow for the unwinding of landowner leases.

6.2. Difference-in-difference results

Fig. 6 shows oil production in Montana and North Dakota from April 2009 to March 2014 within 10 miles of their shared border. Prior to the treatment, oil production in the two states (within the window) appears to follow similar trends, which is confirmed in Table 6. Oil production in both states drifts downward from April 2009 to early 2011 and trends upward from 2011 through mid-2013.

The estimation results for equation (3) are presented in Table 7. The sample period starts one year prior to the regulation change and ends two years after its implementation (April 2011–March 2014). This time period is selected because of the apparent change in production trends beginning in early 2011 (Fig. 6) and the implementation of new regulations in April

Table 7
Oil production Diff-in-Diff results.

	(1)	(2)	(3)	(4)
	LnProd	LnProd	LnProd	LnProd
<i>Treat</i>	0.126 (0.153)	0.133 (0.125)	0.214* (0.125)	0.162 (0.123)
<i>ND</i>	0.375 (0.330)	0.368 (0.327)	0.316 (0.323)	−2.072 (6.494)
<i>Time</i>			−0.002 (0.007)	−0.003 (0.007)
<i>ND × Time</i>				0.004 (0.010)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	2667	2667	2667	2667
<i>R</i> ²	0.051	0.044	0.038	0.038

The dependent variable is the natural log of oil production. Standard errors clustered on operator in parentheses. Estimation results for equation (3). *Treat* is 1 for ND for months after April 2012 and zero for MT and ND before April 2012. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

2014. In the first two columns, which include different time fixed effects, the coefficient estimates for the treatment variable are positive but not statistically indistinguishable from zero at any reasonable level. Although the coefficient estimates are statistically indistinguishable from zero, this does not necessarily imply there is no effect. The 95% confidence interval for the coefficient estimate for the treatment variable in column 1 of Table 7 is [−0.18, 0.43]. Implying that an increase (decrease) in production of more than 0.5% (0.2%) would be needed for our analysis to find an effect. In column 3, the time fixed effects are replaced with a linear time trend, which is restricted to be the same for Montana and North Dakota oil production. The coefficient estimate for the treatment variable becomes positive and significant, which is counter to the expectation that stricter environmental regulations and bond requirements would discourage production in North Dakota. When the linear time trend is allowed to differ across the two states (column 4), the coefficient estimate is no longer significant.

Table 8 presents the results for Equation (3) where the treatment effect is allowed to vary with firm size. Each operator's total oil production in Montana and North Dakota in the year prior to the regulation change (2011) serves as a proxy for its size.¹⁹ Operators are partitioned into quartiles based on their 2011 oil production levels, with quartile one representing the smallest firms and quartile four containing the largest ones. Around half of the firms operate in both states which provides good overlap. In columns 1–4, the coefficient estimate for the treatment variable interacted with the quartile 1 indicator variable is negative and significant at either the 1% or 5% levels. The coefficient estimate in column 1, for example, implies that the regulation change reduced monthly oil production for the smallest firms by 0.46%. This translates to an output reduction of about 17 barrels per year for a typical small producer in North Dakota.²⁰ The results also suggest that the regulation change had a positive and statistically significant effect on oil production for the largest firms (quartile 4). This can be explained by production shifting from smaller to larger firms. Small operators may exit and/or sell existing wells to larger companies, or as smaller firms reduce drilling larger firms drill in their place.

Fig. 7 depicts operator exits within 10-mile windows around the Montana and North Dakota border from April 2009 to March 2012. The vertical axis is the number of firms that exit during a month, where an exit is defined as permanently ceasing oil production for the remainder of the sample period. Operator exits appear to have considerable noise and the number of exits per month are typically zero or one. It is unclear how closely the pre-treatment trends in Montana and North Dakota match up given the level of noise in both series, such as the jump in exits that occur in Montana in August 2010 but no similar increase happens in North Dakota. Generally, the quadratic best fit lines are similar across the two states. The results for equation (4) is presented with this caveat noted.

In Table 9, the estimation results show mixed evidence for whether the regulation change had an effect on the rate of operator exit. In columns 1 and 2, the coefficient estimate for the treatment variable is almost always positive and significant at the 10% level, which implies that the regulation change increased the rate of firm exits. The estimation results are carried out with linear time trends for sake of completeness and despite the clear lack of a linear trend in exits prior to the regulation change. In columns 3 and 4, the coefficient estimates for the treatment variable remain positive but are no longer statistically indistinguishable from zero any reasonable significance level.

In Table 10, where the treatment effect is allowed to vary across firm size, the results are generally consistent with Table 9. The coefficient estimates for the treatment variable interacted with the quartile 1 indicator variable are positive and statistically

¹⁹ Given that unconventional wells have very steep decline curves for oil production, firms need to continually drill new wells in order to maintain production. Thus production in one year is more highly correlated with wells drilled that year. Conventional wells, whose decline curve is less steep, leads to past drilling being strongly correlated with current production. Further, that not all firms that operate in the Bakken are public, making it difficult to find other measures of firms size. We feel that recent production is the best publicly available proxy for size of firm.

²⁰ Operators in quartile 1 in ND averaged 10 barrel per day of oil production in 2011: $3650 \times 0.046\% = 17$.

Table 8

Oil production Diff-in-Diff results effects by firm size.

	(1) LnProd	(2) LnProd	(3) LnProd	(4) LnProd
<i>Treat</i> × Q1	−0.461*** (0.136)	−0.485*** (0.156)	−0.370** (0.148)	−0.414** (0.197)
<i>Treat</i> × Q2	−0.521 (0.456)	−0.538 (0.468)	−0.457 (0.463)	−0.508 (0.480)
<i>Treat</i> × Q3	0.209 (0.416)	0.192 (0.439)	0.287 (0.417)	0.239 (0.396)
<i>Treat</i> × Q4	0.753** (0.334)	0.737** (0.338)	0.829** (0.335)	0.781** (0.370)
<i>ND</i>	0.326 (0.325)	0.338 (0.328)	0.278 (0.321)	−1.920 (6.959)
<i>Time</i>			−0.001 (0.007)	−0.001 (0.008)
<i>ND</i> × <i>Time</i>				0.004 (0.011)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	2494	2494	2494	2494
<i>R</i> ²	0.087	0.094	0.081	0.081

The dependent variable is the natural log of oil production. Standard errors clustered on operator in parentheses. Estimation results for equation (3). *Treat* is 1 for ND for months after April 2012 and zero for MT and ND before April 2012. Q1 – Q4 are indicator variables for firm's production quartile in 2011, the year before the regulation changed. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

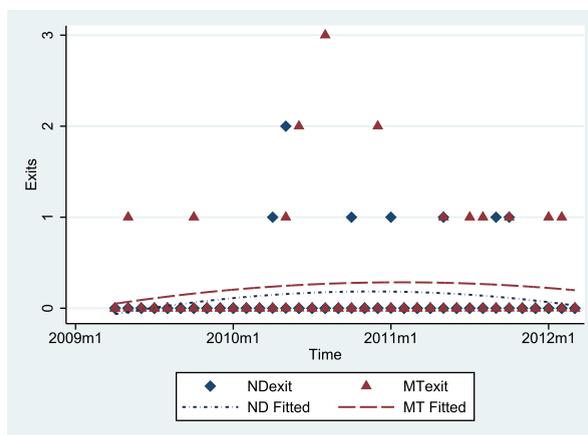


Fig. 7. Operator Exits in 10-mile window of MT-ND Border (April 2009–March 2012). This figure shows the number of rms exiting the MT and ND oil industry. It reveals the pattern of rm exit over time. Exit is dened as last month that an operator had a producing oil well within the 10 mile window around the MT-ND border.

significantly different from zero at the 10% level. For the remaining quartiles, the coefficient estimates are smaller in magnitude and not significantly different from zero at a significance level of 10% or less. These results suggest the regulation change led to an exit by relatively smaller firms but had no impact on the rate of exit by larger firms. However, two important caveats for these results are 1) it is unclear that pre-treatment trends are parallel (Fig. 7). Additionally, the results are somewhat sensitive to changes in the sample period. When varying the sample period to April 2011–March 2013 (Table 29 of Appendix C), the coefficient estimates are marginally significant (p -values ≈ 0.11), yet the coefficient estimates are fairly stable. A Cox Proportional Hazard model given in Table 31 of Appendix D provides a similar magnitude in the likelihood to exit.

6.3. Implications

While the increased well bonding and waste disposal requirements in North Dakota has not seemed to change the number of wells drilled or production, it has seemed to change the structure of the industry. The goal of this section is to test for implications of this change in the industry. One possible impact of a change in the operator structure in ND is a change rent distribution between operators and their input suppliers. Unfortunately, the input costs by well or operator, such as drilling rig rates or bonus bid payments to mineral rights owners, are not publicly available.

Table 9
Firm exit Diff-in-Diff results.

	(1) Exit	(2) Exit	(3) Exit	(4) Exit
<i>Treatment</i>	0.0087* (0.0051)	0.0085* (0.0048)	0.0067 (0.0048)	0.0053 (0.0081)
<i>ND</i>	-0.0014 (0.0033)	-0.0013 (0.0031)	-0.0005 (0.0030)	-0.0437 (0.2033)
<i>Time</i>			0.0004*** (0.0001)	0.0004*** (0.0001)
<i>ND × Time</i>				0.0001 (0.0003)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	4874	4874	4874	4874
<i>R</i> ²	0.020	0.006	0.007	0.007

The dependent variable is the number of firms exiting the industry. Standard errors clustered on operator in parentheses. Estimation results for equation (4) *Treat* is 1 for ND for months after April 2012 and zero for MT and ND before April 2012. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 10
Firm exit Diff-in-Diff results by firm size.

	(1) Exit	(2) Exit	(3) Exit	(4) Exit
<i>Treat × Q1</i>	0.0399* (0.0223)	0.0410* (0.0229)	0.0410* (0.0231)	0.0402 (0.0250)
<i>Treat × Q2</i>	0.0072 (0.0120)	0.0084 (0.0125)	0.0083 (0.0127)	0.0074 (0.0177)
<i>Treat × Q3</i>	0.0050 (0.0089)	0.0057 (0.0081)	0.0056 (0.0082)	0.0047 (0.0107)
<i>Treat × Q4</i>	0.0099 (0.0086)	0.0109 (0.0081)	0.0109 (0.0080)	0.0100 (0.0102)
<i>ND</i>	-0.0033 (0.0034)	-0.0037 (0.0032)	-0.0037 (0.0030)	-0.0313 (0.2282)
<i>Time</i>			0.0003** (0.0001)	0.0003** (0.0001)
<i>ND × Time</i>				0.0000 (0.0004)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	3644	3644	3644	3644
<i>R</i> ²	0.029	0.012	0.012	0.012

The dependent variable is the number of firms exiting the industry. Standard errors clustered on operator in parentheses. *Treat* is 1 for ND for months after April 2012 and zero for MT and ND before April 2012. Q1 – Q4 are indicator variables for firm's production quartile in 2011, the year before the regulation changed. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

One possible change that is testable is the time between the end of drilling and the start of production. Fewer small operators in the industry in ND may lead to a change in the amount of time between drilling is finalized and production starts due to monopsonistic/oligopsonistic behavior from operators in their interactions with firms that complete the well (the fracking of the well). When a buyer has market power, they use their bargaining power by reducing the quantity purchased in order to bring down the price (Murray, 1995). In this case, if the North Dakota regulations increased the market power of operators in purchasing completion services we would expect a longer amount of time between when drilling is finished and production starts. As operators offer to buy less completion services, we would expect the time between the end of drilling and the start of production to increase. To test this hypothesis, a difference-in-difference estimation similar to Equation (3) is estimated. The dependent variable is the time (in months) from the end of drilling to the start of production.

Table 11 shows the treatment effect for wells in North Dakota after the well bonding requirement went into effect. All the treatment effects are positive and statistically different than zero. The Poisson model in Column 3 implies an extra three weeks between the end of drilling and the start of production, consistent with a theory of market power by the buyers of completion services. Note that monthly dummies are included in the analysis to control for changes in the number of wells that finished drilling in a given month. That said, this result is still just consistent with an oligopsonistic model of operator behavior and other explanation may exist.

A final outcome variable studied is environmental incidents (e.g. oil spills) that occur in drilling. Data on incidents at a very spatially disaggregated level are only available for North Dakota, so a difference-in-difference approach is not possible. The

Table 11
Time between drilling and completion.

	(1) Months	(2) Months	(3) Poisson-Months	(4) Dummy
<i>Treat</i>	1.22*** (0.27)	1.22*** (0.29)	0.78** (0.36)	0.09*** (0.02)
State and Month FE	Yes	Yes	Yes	Yes
Clustering	Well	Drilling Month	Well	Well
<i>N</i>	6308	6308	6308	6308

The dependent variable is the number of months between the end of drilling and the start of production for Columns 1, 2, and 3 and a dummy variable equal to one for wells that took more than 6 months to begin production after drilling was completed in Column 4. Standard errors in parentheses. The variable *Treat* is equal to 1 for wells drilled in ND after April 2012 and zero otherwise. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 12
North Dakota environmental incidents.

	(1) Incident	(2) Incident
<i>Treat</i>	-0.030** (0.015)	-0.030** (0.013)
<i>Time</i>	0.009*** (0.004)	0.009*** (0.003)
Operator FE	Yes	Yes
Rig FE	Yes	Yes
Clustering	Operator	Rig
<i>N</i>	4971	4971

The dependent variable is the number of incidents that occur during drilling a well. Standard errors in parentheses. The variable *Treat* is equal to 1 for April 2012 and onward and zero otherwise. The variable *Time* is a linear time trend. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

effect of the regulation change on the rate of environmental incidents that occur in drilling a well is estimated for only wells in Northern Dakota through an OLS with well operator fixed effects and a time trend.

Table 12 shows the results for estimating the effect of the regulation change on environmental incidents. The regulation is associated with a level shift down in the number of incidents that occur while drilling, which is consistent with higher bond requirements encouraging better safety and exit of relatively unsafe operators.

7. Conclusion

Technological expansion will always force a re-evaluation in the specification of property rights, as explained in the seminal work by Demsetz (1967). The recent shale revolution has significantly altered our ability to extract oil and gas. This has resulted in a change in the way that oil and gas operations are regulated. This analysis asks what impact those new regulations have on firms drilling, production and exit decisions. ND changed its oil regulations to require a higher level of bonding and restrict how firms dispose of waste, both largely fixed costs of production. The main oil basin, the Bakken, is under ND and MT thus we use a RD and difference-in-difference methodology to determine how these new regulations altered firm's decisions in ND with MT as a control. Since the ND-MT border was set long before an oil industry emerged, the border acts as an exogenous discontinuity in treatment. Additionally, restricting the analysis to a short distance around the border helps ensure that other unobservables, like geology, is constant though the standard internal validity concerns still apply.

Results find no change in the pace of drilling nor the level of oil production in ND after the regulations passed relative to MT, however SUTVA assumptions likely make this the upper bound of impacts. However, this average effect masks a change in organization in the oil industry in ND. Small operators are statistically more likely to exit the area of analysis and to reduce the level of production. This effect is countered by an increase in production from large operators. The results imply that larger operators may have benefited from the regulation through reduction competition by raising their rivals costs, an outcome predicted by Salop and Scheffman (1983). Operators in ND after the regulation went into effect seems to be offering fewer wells for completion, resulting in a longer delay between the end of drilling and the start of production. This result is consistent with operators having oligopolistic power due to the exit of small operators in conjunction with the increased fixed costs. The amount of environmental accidents related to oil drilling has decreased in ND since passage of these regulations, though this result is not tested against the amount of MT accidents.

The analysis is externally valid in the author's opinion. While our analysis is specifically in the Bakken, the results are consistent with what related literature is finding about oil drilling decisions. The main issues that determine where oil wells are drilled are the price of oil and the amount of oil present (generally geology) while other factors, like taxes or fees, generally

have a smaller impact (Kellogg et al., 2018; Brown et al., 2018; Boomhower, 2019).²¹ Results here provide useful information for policymakers weighing the costs and benefits of increased environmental regulation. The potentially regulated firms usually argue that proposed regulations will threaten their activities in the relative jurisdiction and argue that this will cost jobs and tax revenue. However, it is difficult for policymakers to find rigorous, objective information on how firms have responded to previous environmental regulations. In this case, the increase bonding requirements and restrictions on drilling waste disposals did not change the pace of economic activity. Unfortunately, this analysis can not reveal whether the change in industrial composition will have long-run consequences for the oil industry in ND. The short-run consequences have been small, if any.

Appendix A

This appendix provides several variations of the RD design discussed in Section 5 and estimates for a difference-in-difference model to complement the RD model. In general, modifications to the sample period, functional forms, and windows do not change the overall conclusion that there is no evidence the regulation change affect drilling activity.

Tables 13 and 14 present the results of a parametric RD estimation of equation (1) using a Poisson model on the count of wells drilled. These tables are similar to that of Tables 3 and 4 except using the count of wells drilled (instead of the log) and a Poisson model.

Tables 15 and 16 present expanded results for the RD estimation in equation (1). In Table 15, the coefficient and standard errors estimates for the assignment variable are shown for well drilling in the two-year period prior to the regulation revisions (April 2010–March 2012). Additionally, the AIC values for each model are included below the standard error estimates. Table 16 presents the coefficient estimates for the sample period following the regulation change (April 2012–March 2014). The window around the Montana–North Dakota border is varied across the columns, and the rows reflect different polynomial orders for the function $f(x_i)$ in equation (1).

Table 17 shows the estimation results for equation (2). The coefficient estimates for the treatment variable (D_{jt}) are presented along with the standard error estimates and AIC values. The sample period for well drilling is April 2010 to March 2014. The columns are different windows around the Montana–North Dakota border, and the rows are specifications with varying polynomial orders.

Tables 18 and 19 contain non-parametric RD results for well drilling in the two years before and two years following the regulation change. The results are generally consistent with Tables 15 and 16 in showing no discontinuity in drilling at the border either prior to or after the regulation revisions.

Table 20 presents the estimation results for equation (2) when the pre-treatment and post-treatment sample periods are limited to April 2010–March 2011 and April 2013–March 2014, respectively. This restricts the sample to drilling activity that occurred 12–24 months before and 12–24 months after the regulation change. It allows for testing whether the regulation had a delayed effect on well drilling. The results are fairly similar to Table 5; there are more coefficient estimates that are negative but none are statistically significant.

Table 22 shows that the estimation results for equation (2), when the latitude fixed effect (γ_i) is excluded, are fairly similar to the results with the fixed effects included.

Table 23 contains the estimation results for equation (2) when the cell size is modified from 1×1 miles to 5×5 miles. The results show little evidence that the regulation revisions had an effect on drilling. For only one window width (50 miles) and one polynomial function (cubic) is the coefficient estimate for the treatment variable negative and statistically indistinguishable from zero.

Table 24 presents the estimation results for equation (1) with the number of wells drilled within the cell in the prior two years (April 2010–March 2012) included as a control. This allows for the possibility that the level of drilling activity within a cell before the regulation change may affect subsequent drilling levels. Cells may have an existing well because they are more economically attractive, and in turn experience more drilling in the following two years. Additionally a cell may become saturated with wells and drilling within the cell may decline. The number of wells previously drilled, and the squared number of wells previously drilled are included as controls. The results consistent with other specifications that show no evidence that the regulation influenced drilling.

Table 25 presents the estimation of a difference-in-differences model with the number of wells drilled as the dependent variable. Results are shown across six different distances around the ND–MT border. The implications are that within 10 miles of the border there is no change in the number of wells drilled as a result of the well bonding requirements. As the distance expands, the underlying geology favors ND and the results bear this out as the results imply an increase in drilling in ND after the increase in well bonds.

²¹ On a technical level, most every paper that has analyzed the economic impact of fracking uses geology as an instrument for where wells are drilled Feyrer et al. (2017); Maniloff and Mastromonaco (2017); Weber (2014) implying that geology is the main driver of drilling decisions.

Table 13
RD Results with Poisson Count Model (April 2010–March 2012).

	20-Mile Window			30-Mile Window		
	(1) Wells	(2) Wells	(3) Wells	(4) Wells	(5) Wells	(6) Wells
Assign. Var. D_i	0.062 (0.054)	−0.013 (0.125)	−0.083 (0.157)	0.111** (0.045)	0.013 (0.094)	−0.011 (0.132)
Poly. Order	Zero	1st	2nd	Zero	1st	2nd
AIC	883.6	917.2	918.8	1369.9	1436.8	1436.6
Clusters	40	40	40	60	60	60
N	354	354	354	546	546	546

Standard errors clustered on force variable (x_i) in parentheses. Specification with lowest AIC is preferred. Constant only models do not include the latitude fixed effect term γ_i .

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 14
RD Results with Poisson Count Model (April 2012–March 2014).

	20-Mile Window			30-Mile Window		
	(1) Wells	(2) Wells	(3) Wells	(4) Wells	(5) Wells	(6) Wells
Assign. Var. D_i	0.358*** (0.099)	−0.141 (0.212)	0.071 (0.334)	0.518*** (0.080)	−0.094 (0.175)	−0.104 (0.272)
Poly. Order	Zero	1st	2nd	Zero	1st	2nd
AIC	1019.8	1012.5	1011.6	1815.5	1739.7	1737.4
Clusters	40	40	40	60	60	60
N	340	340	340	550	550	550

Standard errors clustered on force variable (x_i) in parentheses. Specification with lowest AIC is preferred. Constant only models do not include the latitude fixed effect term γ_i .

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 15
RD Results with Alternative Specifications and Windows (April 2010–March 2012).

Window (Miles)	(1)	(2)	(3)	(4)	(5)	(6)
	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Polynomial Order						
Zero	0.032 (0.064)	0.052 (0.041)	0.088** (0.034)	0.123*** (0.028)	0.196*** (0.029)	0.187*** (0.028)
	192.9	330.0	526.0	951.8	1865.7	2130.2
First	−0.046 (0.157)	0.015 (0.120)	0.020 (0.085)	0.101 (0.064)	0.003 (0.062)	0.063 (0.061)
	105.8	251.5	470.3	949.0	1840.3	2174.9
Second	−0.152 (0.201)	−0.033 (0.154)	0.024 (0.123)	0.030 (0.098)	0.033 (0.098)	−0.071 (0.087)
	103.1	250.1	468.2	947.5	1836.0	2164.9
Third	0.142 (0.392)	−0.060 (0.158)	−0.057 (0.137)	0.023 (0.127)	−0.010 (0.138)	0.092 (0.118)
	100.7	247.6	463.4	949.5	1833.7	2151.1
Fourth	0.377 (0.375)	−0.155 (0.219)	0.005 (0.138)	−0.034 (0.140)	−0.040 (0.150)	−0.066 (0.149)
	87.6	243.1	462.8	950.2	1834.0	2139.0
Fifth	−0.224 (0.499)	0.156 (0.345)	−0.139 (0.193)	−0.080 (0.142)	0.004 (0.155)	−0.075 (0.147)
	85.6	238.3	460.5	944.8	1839.2	2132.9
Sixth	0.239 (0.451)	0.424 (0.319)	0.005 (0.213)	−0.151 (0.164)	0.024 (0.159)	0.014 (0.157)
	81.4	241.8	467.5	952.0	1833.1	2137.2
Clusters	20	40	60	97	124	145
N	192	354	546	964	1519	1724

Estimation includes data on well drilling from April 2010 to March 2012. Coefficient estimates for the assignment variable (D_j) in equation (1). Standard errors clustered on cell distance in parentheses; AIC values shown below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 16
RD Results with Alternative Specifications and Windows (April 2012–March 2014).

Window (Miles)	(1) LnWells 10	(2) LnWells 20	(3) LnWells 30	(4) LnWells 50	(5) LnWells 75	(6) LnWells 100
Polynomial Order						
Zero	−0.093 (0.192) 140.4	0.222* (0.128) 472.4	0.269*** (0.098) 845.7	0.506*** (0.065) 1622.3	0.584*** (0.054) 2799.1	0.560*** (0.052) 3049.4
First	0.003 (0.332) 139.7	−0.138 (0.202) 462.1	−0.063 (0.146) 823.8	0.023 (0.109) 1581.1	0.184* (0.103) 2759.5	0.269** (0.106) 3056.0
Second	0.379 (0.333) 133.1	0.025 (0.309) 460.2	−0.097 (0.238) 820.7	−0.101 (0.170) 1579.8	−0.112 (0.148) 2743.4	−0.121 (0.137) 3004.3
Third	0.674* (0.337) 129.4	0.402 (0.262) 452.9	0.096 (0.293) 817.7	−0.104 (0.235) 1579.8	−0.000 (0.194) 2743.8	−0.040 (0.188) 3005.7
Fourth	1.016** (0.464) 216.3	0.650** (0.243) 504.8	0.427* (0.233) 923.3	0.062 (0.275) 1719.2	−0.154 (0.253) 2890.8	−0.037 (0.232) 3123.8
Fifth	1.562 (1.016) 124.6	0.825*** (0.272) 450.4	0.597*** (0.206) 810.8	0.278 (0.254) 1578.9	0.106 (0.268) 2743.6	−0.159 (0.288) 3007.0
Sixth	0.128 (1.386) 119.7	1.096*** (0.331) 451.6	0.902*** (0.187) 810.8	0.422* (0.239) 1576.8	0.254 (0.270) 2743.7	0.246 (0.258) 3001.7
Clusters	20	40	60	99	131	147
N	150	340	550	964	1513	1648

Estimation includes data on well drilling from April 2012 to March 2014. Coefficient estimates for the assignment variable (D_j) in equation (1). Standard errors clustered on cell distance in parentheses; AIC values shown below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 17
RD Results with Alternative Specifications and Windows (April 2010–March 2014).

Window (Miles)	(1) LnWells 10	(2) LnWells 20	(3) LnWells 30	(4) LnWells 50	(5) LnWells 75	(6) LnWells 100
Polynomial Order						
Zero	−0.021 (0.109) 409.5	0.223*** (0.073) 877.6	0.308*** (0.060) 1569.0	0.348*** (0.045) 2866.1	0.333*** (0.039) 4983.1	0.330*** (0.038) 5487.7
First	0.098 (0.266) 308.9	−0.098 (0.182) 759.2	−0.020 (0.137) 1368.7	0.072 (0.103) 2666.8	0.322*** (0.090) 4752.6	0.308*** (0.088) 5365.4
Second	0.407 (0.238) 303.0	0.035 (0.282) 756.4	−0.151 (0.206) 1366.3	−0.117 (0.170) 2653.1	0.001 (0.135) 4727.2	0.093 (0.128) 5293.6
Third	0.513* (0.271) 289.0	0.478* (0.260) 744.1	0.026 (0.264) 1358.1	−0.199 (0.236) 2652.2	−0.029 (0.191) 4725.9	−0.105 (0.179) 5273.0
Clusters	20	40	60	100	133	155
N	342	694	1096	1928	3032	3372

Estimation includes data on well drilling from April 2010 to March 2014. Coefficient estimates for the treatment variable (D_{jt}) in equation (2). Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 18
Non-Parametric RD Results (April 2010–March 2012).

	(1)	(2)	(3)	(4)	(5)	(6)
Window (Miles)	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Bandwidth						
lwald	−0.016 (0.212)	−0.015 (0.203)	−0.015 (0.194)	−0.015 (0.190)	−0.015 (0.187)	−0.015 (0.188)
lwald50	0.078 (0.271)	0.078 (0.271)	0.078 (0.271)	0.078 (0.271)	0.078 (0.271)	0.078 (0.271)
lwald200	−0.046 (0.130)	−0.051 (0.129)	−0.058 (0.127)	−0.065 (0.124)	−0.068 (0.122)	−0.068 (0.122)
N	192	354	546	964	1519	1724

Estimation includes data on well drilling from April 2012 to March 2014. Coefficient estimates for the assignment variable (D_j) for non-parametric RD. lwald is the optimal bandwidth based on minimizing MSE. Standard errors clustered on cell distance in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 19
Non-Parametric RD Results (April 2012–March 2014).

	(1)	(2)	(3)	(4)	(5)	(6)
Window (Miles)	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Bandwidth						
lwald	0.738*** (0.279)	0.604 (0.377)	0.604 (0.377)	0.604 (0.377)	0.604 (0.377)	0.604 (0.377)
lwald50	0.604 (0.377)	0.492** (0.234)	0.492** (0.234)	0.492** (0.234)	0.492** (0.234)	0.492** (0.234)
lwald200	0.386** (0.196)	0.645** (0.258)	0.627** (0.250)	0.655** (0.263)	0.638** (0.255)	0.647** (0.259)
N	150	340	550	964	1513	1648

Estimation includes data on well drilling from April 2012 to March 2014. Coefficient estimates for the assignment variable (D_j) for non-parametric RD. lwald is the optimal bandwidth based on minimizing MSE. Standard errors clustered on cell distance in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 20
RD Results- Well Drilling for April 2010–March 2011 and April 2013–March 2014.

	(1)	(2)	(3)	(4)	(5)	(6)
Window (Miles)	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Polynomial Order						
Zero	−0.073 (0.150)	0.213* (0.113)	0.296*** (0.088)	0.371*** (0.066)	0.418*** (0.060)	0.409*** (0.060)
	191.8	412.3	742.7	1381.3	2468.8	2722.9
First	−0.315 (0.404)	−0.177 (0.398)	0.107 (0.263)	0.132 (0.156)	0.258* (0.134)	0.301** (0.130)
	64.3	292.1	614.6	1260.5	2363.1	2686.1
Second	−1.251 (0.780)	−0.560 (0.556)	−0.442 (0.435)	−0.109 (0.288)	0.023 (0.222)	−0.043 (0.205)
	56.5	288.9	605.5	1256.7	2345.9	2634.2
Third	0.820 (0.960)	−0.183 (0.691)	−0.573 (0.622)	−0.271 (0.434)	−0.094 (0.314)	−0.202 (0.294)
	35.4	276.5	600.2	1253.7	2343.9	2633.1
Clusters	20	40	60	98	126	142
N	172	365	566	1030	1659	1872

Estimation includes data on wells drilled for April 2010–March 2011 and April 2013–March 2014. Coefficient estimates for the treatment variable (D_{jt}) in equation (2). Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 21
RD Results with Alternative Specifications and Windows (April 2009–March 2015).

	(1)	(2)	(3)	(4)	(5)	(6)
Window (Miles)	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Polynomial Order						
Zero	−0.021 (0.103)	0.229*** (0.073)	0.319*** (0.063)	0.358*** (0.045)	0.336*** (0.039)	0.327*** (0.038)
	479.2	987.9	1694.7	3073.2	5451.7	6090.0
First	0.115 (0.259)	−0.059 (0.186)	0.012 (0.141)	0.073 (0.104)	0.309*** (0.090)	0.316*** (0.088)
	381.9	873.0	1492.3	2862.7	5195.2	5952.1
Second	0.425 (0.259)	0.112 (0.273)	−0.092 (0.207)	−0.103 (0.178)	−0.018 (0.136)	0.085 (0.128)
	377.9	869.2	1488.4	2851.4	5165.7	5883.2
Third	0.753*** (0.255)	0.617*** (0.220)	0.102 (0.249)	−0.155 (0.240)	−0.051 (0.188)	−0.114 (0.179)
	367.6	855.1	1479.0	2850.6	5164.3	5854.0
Clusters	20	40	60	100	134	157
N	374	745	1168	2053	3306	3721

Estimation includes data on well drilling from April 2009 to March 2015. Coefficient estimates for the treatment variable (D_{jt}) in equation (2). Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 22
RD Results without Latitude Fixed Effects (April 2010–March 2014).

	(1)	(2)	(3)	(4)	(5)	(6)
Window (Miles)	LnWells 10	LnWells 20	LnWells 30	LnWells 50	LnWells 75	LnWells 100
Polynomial Order						
Zero	−0.021 (0.109)	0.223*** (0.073)	0.308*** (0.060)	0.348*** (0.045)	0.333*** (0.039)	0.330*** (0.038)
	409.5	877.6	1569.0	2866.1	4983.1	5487.7
First	0.230 (0.208)	−0.097 (0.168)	−0.010 (0.124)	0.175* (0.090)	0.339*** (0.081)	0.338*** (0.080)
	407.0	862.6	1518.4	2829.9	4908.2	5457.7
Second	0.492*** (0.168)	0.125 (0.226)	−0.063 (0.206)	−0.055 (0.152)	0.029 (0.118)	0.118 (0.113)
	410.3	862.1	1524.1	2816.1	4895.9	5415.1
Third	0.756*** (0.198)	0.573*** (0.175)	0.164 (0.233)	−0.126 (0.220)	−0.104 (0.172)	−0.126 (0.163)
	412.0	861.1	1524.4	2823.0	4897.3	5410.8
Clusters	20	40	60	100	133	155
N	342	694	1096	1928	3032	3372

Coefficient estimates for the treatment variable (D_{jt}) in equation (2) when the fixed. Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 23
RD Results with 5 × 5 Mile Cell Dimensions (April 2010–March 2014).

Window (Miles)	(1) LnWells 50	(2) LnWells 75	(3) LnWells 100	(4) LnWells 125	(5) LnWells 150	(6) LnWells 200
Polynomial Order						
Zero	0.163 (0.122) 1581.8	0.211* (0.111) 2373.6	0.199* (0.108) 2690.6	0.205* (0.109) 2761.8	0.188* (0.108) 2819.0	0.173* (0.099) 2915.6
First	0.073 (0.240) 1386.4	0.155 (0.200) 2147.3	0.143 (0.189) 2500.6	0.180 (0.187) 2594.1	0.098 (0.187) 2666.2	0.075 (0.156) 2757.6
Second	–0.254 (0.328) 1354.3	0.108 (0.288) 2129.2	0.166 (0.268) 2422.3	0.258 (0.262) 2484.4	0.166 (0.245) 2568.3	0.121 (0.222) 2703.9
Third	–1.004*** (0.343) 1350.2	–0.256 (0.373) 2118.1	–0.228 (0.306) 2414.3	0.016 (0.321) 2481.0	–0.065 (0.295) 2545.9	–0.026 (0.242) 2648.1
Clusters	20	29	36	41	50	63
N	596	872	980	1000	1020	1062

Coefficient estimates for the treatment variable (D_{jt}) in equation (2) when the cell size is modified to 5 × 5 miles. Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 24
RD Results April 2012–March 2014 with Pre-treatment Drilling Controls.

	(1) Wells Linear LnWells	(2) Wells Quadratic LnWells	(3) Wells Linear LnWells	(4) Wells Quadratic LnWells
Polynomial Order				
Zero	0.269*** (0.072) 517.2	0.271*** (0.072) 517.3	0.269*** (0.072) 517.2	0.271*** (0.072) 517.3
First	–0.122 (0.161) 504.7	–0.113 (0.162) 505.5	–0.139 (0.203) 461.3	–0.131 (0.202) 460.9
Second	0.100 (0.222) 505.3	0.096 (0.225) 506.4	0.026 (0.308) 459.4	0.027 (0.313) 458.9
Third	0.463** (0.189) 503.0	0.459** (0.191) 504.1	0.407 (0.258) 452.0	0.407 (0.265) 451.6
Latitude FE	No	No	Yes	Yes
Clusters	40	40	40	40
N	340	340	340	340

Coefficient estimates for the treatment variable (D_{jt}) in equation (1) with 20-mile window. The number of wells drilled during the prior 2 years are included as controls in either linear or quadratic forms. Standard errors clustered on cell distance in parentheses; AIC values below standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 25
Difference-in-Difference Estimates for Varying Distances around the ND-MT Border.

	(1) 10 Miles lnSpuds	(2) 20 Miles lnSpuds	(3) 30 Miles lnSpuds	(4) 40 Miles lnSpuds	(5) 50 Miles lnSpuds	(6) 60 Miles lnSpuds
treat	–0.021 (0.103)	0.229*** (0.073)	0.319*** (0.063)	0.358*** (0.045)	0.336*** (0.039)	0.327*** (0.038)
N	374	745	1168	2053	3306	3721
AIC	479.2	987.9	1694.7	3073.2	5451.7	6090.0

Robust standard errors in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix B

This appendix describes the results of a slightly different RD method to estimating the effect of the regulation change on drilling activity. [Wing and Cook \(2013\)](#) introduce a modified RD approach, which they call “pretest RDD”, that incorporates pre-treatment observations. The authors note that if the underlying functional relationship between the outcome and force variables is stable, the pretest RDD can improve identification relative to the standard RD design. This occurs because pre-treatment observations may contain information on the underlying relationship between the force variable and outcome variable.

This method requires a pre-treatment period, where no observations received the treatment, and a post-treatment period, where only observations above a cutoff receive the treatment. For a parametric RD, the first step involves estimating a polynomial function for all untreated observations, which includes drilling activity in cells observed in Montana and North Dakota prior to the treatment (April 2010–March 2012). This estimation equation is shown in Equation (1) and includes an indicator variable for the State ($S_i = 0$ if MT; $S_i = 1$ if ND) and an indicator variable for the time period ($t = 0$ if pre-treatment; $t = 1$ if post-treatment). The function $f(x)$ denotes a polynomial function, which varies from a zero degree to quadratic polynomial in different specifications.

$$\text{LnWells}_{it}(0) = \beta S_i + \gamma T_t + f(x_i) + \epsilon_{it} \quad (5)$$

The second step is to estimate a polynomial function for the treated observations, which includes only drilling in ND cells following the regulation change. This is carried out in Equation (2), where $g(x_i)$ is a polynomial function. The third and final step is to estimate the treatment at the cutoff. This is done by calculating the difference between the fitted value at the cutoff from the polynomial regression in Equation (6) and the fitted value at the cutoff from the polynomial regression Equation (5).

$$\text{LnWells}_{it}(1) = g(x_i) + \epsilon_{it} \quad (6)$$

[Table 26](#) presents the pretest RDD results for three polynomial regressions (zero degree to quadratic) for a 20-mile window and 30-mile window on each side of the MT-ND boundary. The first and second columns presents the fitted values at the cutoff from the untreated and treated sample polynomial regressions, respectively. The third column shows the difference in the fitted values and the corresponding z-statistic for the difference in the fitted values. The fourth, fifth, and sixth columns display results for a 30-mile window. Overall, the results are very similar to in [Table 5](#) and show no evidence of an effect on drilling activity.

Table 26
Cook and Wing Pretest RDD Results.

	20-Mile Window			30-Mile Window		
	Treated: Fitted Value at Cutoff	Untreated: Fitted Value at Cutoff	Difference	Treated: Fitted Value at Cutoff	Untreated: Fitted Value at Cutoff	Difference
Zero Order	0.238 (0.057)	0.461 (0.048)	0.223 (0.075)	0.28 (0.044)	0.588 (0.044)	0.308*** (0.062)
1st Order	0.295 (0.138)	0.198 (0.112)	-0.097 (0.178)	0.203 (0.099)	0.193 (0.081)	-0.01 (0.127)
2nd Order	0.155 (0.257)	0.28 (0.137)	0.125 (0.291)	0.306 (0.178)	0.243 (0.151)	-0.063 (0.233)
N	694	694	694	1096	1096	1096

Bootstrapped standard errors in parentheses. Standard errors are clustered on cell distance and estimated through 500 replications.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix C

Table 27
Oil Production Diff-in-Diff Results- Effects by Firm Size (April 2010–March 2013).

	(1) LnProd	(2) LnProd	(3) LnProd	(4) LnProd	(5) LnProd
<i>Treat</i> × Q1	-0.400*** (0.138)	-0.374** (0.158)	-0.347** (0.141)	-0.671*** (0.195)	-0.672*** (0.197)
<i>Treat</i> × Q2	-0.354 (0.414)	-0.332 (0.426)	-0.335 (0.415)	-0.700 (0.428)	-0.659 (0.433)
<i>Treat</i> × Q3	0.525 (0.412)	0.546 (0.433)	0.562 (0.409)	0.219 (0.364)	0.236 (0.364)
<i>Treat</i> × Q4	1.012*** (0.351)	1.035*** (0.358)	1.046*** (0.349)	0.697* (0.357)	0.714* (0.359)
ND	0.116 (0.307)	0.106 (0.310)	0.101 (0.305)	-11.242** (5.476)	-207.974 (169.255)

(continued on next page)

Table 27 (continued)

	(1) LnProd	(2) LnProd	(3) LnProd	(4) LnProd	(5) LnProd
<i>Time</i>			0.003 (0.006)	−0.000 (0.006)	0.255 (0.301)
<i>ND × Time</i>				0.018** (0.009)	0.648 (0.541)
<i>Time</i> ²					−0.000 (0.000)
<i>ND × Time</i> ²					−0.001 (0.000)
Time FE	Month	Year	None	None	None
Operator FE	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3306	3306	3306	3306	3306
<i>R</i> ²	0.085	0.095	0.080	0.085	0.091

Table shows results for equation (3) with the sample period varied. Standard errors clustered on operator are shown in parentheses. The dependent variable is the natural log of monthly oil production. The sample period is April 2010 to March 2013. Q1, Q2, Q3, and Q4 are indicator variables for firm size quartiles.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 28

Oil Production Diff-in-Diff Results- Effects by Firm Size (April 2009–March 2013).

	(1) LnProd	(2) LnProd	(3) LnProd	(4) LnProd	(5) LnProd
<i>Treat × Q1</i>	−0.364** (0.170)	−0.326* (0.190)	−0.322* (0.163)	−0.725*** (0.214)	−0.672*** (0.197)
<i>Treat × Q2</i>	−0.294 (0.395)	−0.262 (0.407)	−0.284 (0.394)	−0.730* (0.419)	−0.659 (0.433)
<i>Treat × Q3</i>	0.696 (0.426)	0.730 (0.447)	0.725* (0.416)	0.313 (0.369)	0.236 (0.364)
<i>Treat × Q4</i>	1.142*** (0.374)	1.175*** (0.382)	1.166*** (0.374)	0.740** (0.364)	0.714* (0.359)
<i>ND</i>	0.029 (0.298)	0.017 (0.301)	0.020 (0.297)	−11.411** (4.820)	−207.974 (169.255)
<i>Time</i>			0.002 (0.005)	−0.001 (0.005)	0.255 (0.301)
<i>ND × Time</i>				0.019** (0.008)	0.648 (0.541)
<i>Time</i> ²					−0.000 (0.000)
<i>ND × Time</i> ²					−0.001 (0.000)
Time FE	Month	Year	None	None	None
Operator FE	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4021	4021	4021	4021	3306
<i>R</i> ²	0.085	0.094	0.081	0.090	0.091

Table shows results for equation (3) with the sample period varied. Standard errors clustered on operator are shown in parentheses. The dependent variable is the natural log of monthly oil production. The sample period is April 2009 to March 2013. Q1, Q2, Q3, and Q4 are indicator variables for firm size quartiles.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 29
Firm Exit Diff-in-Diff Results- Effects by Firm Size (April 2011–March 2013).

	(1) Exit	(2) Exit	(3) Exit	(4) Exit
<i>Treat</i> × Q1	0.0404 (0.0253)	0.0430 (0.0261)	0.0429 (0.0265)	0.0428 (0.0290)
<i>Treat</i> × Q2	0.0052 (0.0141)	0.0078 (0.0145)	0.0075 (0.0147)	0.0074 (0.0217)
<i>Treat</i> × Q3	0.0044 (0.0106)	0.0066 (0.0093)	0.0063 (0.0095)	0.0061 (0.0130)
<i>Treat</i> × Q4	0.0087 (0.0100)	0.0111 (0.0090)	0.0109 (0.0087)	0.0108 (0.0124)
<i>ND</i>	−0.0013 (0.0057)	−0.0028 (0.0051)	−0.0026 (0.0049)	−0.0088 (0.4128)
<i>Time</i>			0.0005** (0.0002)	0.0005** (0.0002)
<i>ND</i> × <i>Time</i>				0.0000 (0.0007)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	2639	2639	2639	2639
<i>R</i> ²	0.029	0.011	0.011	0.011

Table shows results for equation (4) with the sample period varied. Standard errors clustered on operator are shown in parentheses. The dependent variable is an indicator variable for operator exit from state. The sample period is April 2011 to March 2013. Q1, Q2, Q3, and Q4 are indicator variables for firm size quartiles.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 30
Firm Exit Diff-in-Diff Results- Effects by Firm Size (April 2009–March 2013).

	(1) Exit	(2) Exit	(3) Exit	(4) Exit
<i>Treat</i> × Q1	0.0384* (0.0212)	0.0392* (0.0217)	0.0399* (0.0219)	0.0408* (0.0228)
<i>Treat</i> × Q2	0.0063 (0.0110)	0.0072 (0.0115)	0.0078 (0.0117)	0.0088 (0.0144)
<i>Treat</i> × Q3	0.0054 (0.0086)	0.0059 (0.0080)	0.0065 (0.0079)	0.0074 (0.0087)
<i>Treat</i> × Q4	0.0088 (0.0082)	0.0095 (0.0078)	0.0102 (0.0077)	0.0111 (0.0086)
<i>ND</i>	−0.0023 (0.0022)	−0.0026 (0.0021)	−0.0028 (0.0020)	0.0225 (0.1103)
<i>Time</i>			0.0002*** (0.0001)	0.0003*** (0.0001)
<i>ND</i> × <i>Time</i>				−0.0000 (0.0002)
Time FE	Month	Year	None	None
Operator FE	Yes	Yes	Yes	Yes
<i>N</i>	4652	4652	4652	4652
<i>R</i> ²	0.030	0.013	0.012	0.012

Table shows results for equation (4) with the sample period varied. Standard errors clustered on operator are shown in parentheses. The dependent variable is an indicator variable for operator exit from state. The sample period is April 2009 to March 2013. Q1, Q2, Q3, and Q4 are indicator variables for firm size quartiles.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix D

This appendix provides the results of a duration analysis approach to estimating the effects of the regulation change on firm exit. Duration analysis (or hazard modeling) is well suited for evaluating firm exit because it allows the rate of exit to be time dependent and can account for censored data. Equation (3) is a Cox proportional hazard model for an operator's exit from a state. An operator is considered to exit a state when they shutdown production within the 10-mile window of the MT-ND boundary and do not restart production for the remainder of the sample period. The hazard function and baseline hazard function are denoted by $h(t)$ and $h_0(t)$, respectively. The variable D is the treatment variable, which is equal to one for operator production in North Dakota and equal to zero for operator production in Montana.

$$h(t) = h_0(t)\exp(\beta D) \quad (7)$$

Table 31 presents the results of two variations of the Cox proportional hazard model in Equation (7). This table shows exponentiated coefficient estimates, where a value greater than one suggests there is a positive correlation between the regulation change and the probability of firm exit; conversely, a coefficient estimate less than one implies the a negative correlation with the probability of exit (i.e. prolongs the survival of the firm). Column 1, which presents the hazard model results with the treatment dummy as the sole explanatory variable, shows the regulation change is associated with a higher rate of firm exit. In column 2, where the baseline hazard function ($h_0(t)$) is allowed to vary by operator, the coefficient estimate for the treatment variable is similar and statistically significant at the 10% level. The exponentiated coefficient shown implies a 9% higher likelihood to exiting after the increase in well bonding.

Table 31
Firm Exit Hazard Model Analysis.

	(1) Basic Cox Proportional	(2) Stratified by Operator
<i>Treat</i>	2.487** (1.130)	3.000* (1.685)
Log Likelihood	−97.1	−4.5
<i>N</i>	101	101

Robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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