Experiential Gains with a New Technology: An Empirical Investigation of Hydraulic Fracturing

Timothy Fitzgerald

In conjunction with technologies such as horizontal drilling, hydraulic fracturing has transformed U.S. and world energy outlooks by adding reserves from unconventional resources. Fracturing was developed by experimentation and experience. This study empirically analyzes fracturing data for wells in the Williston Basin in North Dakota and Montana, focusing on firms' ability to improve well production over time through collaboration. Results suggest that producers gain from experience with fracturing and that proprietary additives are not generally correlated with greater production but have value for some firms. Experiential gains are stronger for operators than for contractors, but some operator-contractor pairings have productive value.

Key Words: Bakken shale, experiential gains, hydraulic fracturing, oil and gas, technological change, unconventional resources

Hydraulic fracturing (known as fracing within the industry and fracking to general audiences), though controversial, has been widely cited as a transformative technology for the U.S. oil and gas sector (e.g., Rogers 2011, Jacoby, O'Sullivan, and Paltsev 2012).[1] In conjunction with other technologies, such as horizontal drilling and multidimensional seismography, hydraulic fracturing has helped to transform the global energy outlook by adding oil and gas reserves from unconventional resources and has boosted production. Oil production in the United States has rebounded to levels not seen since the

[1] Concerns about environmental and regional impacts of widespread development permeate the debate, and work to identify and value those environmental impacts is ongoing. Here, the focus is on productivity gains and is germane to the environmental debate insofar as it can quantify the gains from fracturing against which environmental costs should properly be accounted.

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1980s. And nowhere has the effect of unconventional resource extraction been as emphatic as in North Dakota, which rose from sixth to second in the ranks of oil-producing states between 2009 and 2014.

This study provides an empirical analysis of job-specific data on fracturing of wells in the Williston Basin of North Dakota and Montana and focuses on the role of experience with this new technology in increasing production as it is more widely applied.[2] This study also explores the role of proprietary information in the process of improving production.

In the oil and gas sector, investment and production decisions are ultimately made by well operators, which are usually private oil and gas firms. Barriers to entry are relatively low so multiple firms compete for acreage and employees who have expertise in engineering and geology. Contractors that provide pressure pumping and well servicing are also important to the development and adoption of fracturing. In the past, the number of firms that provided such services was small—in 2003, the Environmental Protection Agency (EPA) signed a memorandum with just three firms in its effort to limit use of specific chemical additives in fracturing fluid. Those three firms dominated the market at the time, and Rogers (2011) reported that the three firms enjoyed a 75 percent market share as recently as 2010. By contrast, in the data examined here, those firms have less than two-thirds of the market and the share declines annually. Contractors typically work with many operators, placing them in a position as potentially valuable partners.[3] And as unconventional resources have become more important, the number of providers competing to help enhance well productivity has increased. The estimation sample introduced in this study includes twelve contractors.

The productivity gains stemming from relationship-specific pairings of operators and contract drillers in the oil and gas industry are economically significant (Kellogg 2011). Some operators design their own well completions, including fracturing and injected fluids. Completion contractors have developed formulas for fracturing jobs, which they can sell to operators. These “recipes” may include toxic chemicals that are intended to increase production but may also create environmental risks. Some contractors have been vociferous defenders of the need to protect the recipes through nondisclosure agreements because they consider them trade secrets. This study considers how the relationship between operators and contractors may be affected by experience with the technology and resulting trade secrets.

Using detailed information about well completions, this study empirically summarizes how operators and contractors have learned from experience and the role of undisclosed additives in that learning. The success of a new formula is ultimately measured in terms of how much oil the well produces.[4] This

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[2] Hefner (2014) identified private mineral ownership, relatively lenient regulations, and well-developed capital markets as reasons why the United States spawned the unconventional resource revolution. This investigation is of gains over a relatively short time horizon after fracturing had been widely applied to a new resource basin.

[3] It is not possible to distinguish operational control from ownership with the data used in the analysis. The operator is designated as the principal party but can represent a collection of firms that potentially includes contractors. The contracts between operators and contractors vary: piece rate, fixed fee, partnerships (farm-ins), and combinations are all used. Specific contractual terms are not observed here—only designated operators and primary contractors.

[4] Although wells in the Bakken produce associated natural gas, the oil/gas ratio and relative prices of the two products during the period examined were such that oil dominated the value of production.

study connects completion to subsequent production by linking well-specific information from the FracFocus chemical disclosure registry, a joint venture of the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission (*www.fracfocus.org*), with public production records. Though changes in costs and environmental risks may also be important, they are not measured. Matching production records with reported completion treatments allows for an assessment of gains from advances in technical refinements and experience. The empirical analysis addresses experiential gains for three types of firms—operators, contractors, and operator-contractor pairs—and allows for general diffusion gains.

Covert (2014) is a related study of technological change and learning in development of unconventional oil and gas in North Dakota. Those results indicated that operators have left money on the table by failing to adopt the most productive frac recipes and that learning has been passive rather than experimental. Four notable differences between that study and this one are useful to keep in mind. The time periods of the data are different; this study analyzes wells completed more recently and includes wells in North Dakota and Montana that overlie similar resources in the Williston Basin. It also takes a broader view of how learning and diffusion may occur by including completion contractors (the analysis is limited to the Bakken formation and does not account for potential spillovers from other formations and plays). Finally, it includes a larger number of elements of the fracturing recipes and associated trade secret provisions rather than focusing on sand and water. Undisclosed additives have been controversial because of concern about toxicity, but firms presumably try to protect secret additives because they believe they improve results and have lobbied for continuation of these protections.

Another related study, Chermak, Crafton, and Patrick (2012), examined differential productivity effects of fracking in vertical and horizontal wells and estimated a system of equations for cumulative production of oil and gas, creation of fractures, and fracture conductivity. The main results of that study indicate large variability in the effectiveness of completion methods. Because one cannot predict the outcome (production) of a particular fracturing job perfectly, operators and contractors continue to experiment, which may affect their estimates of available reserves. The data set used in this study provides information about a relatively large sample from a reasonably uniform geologic formation but does not include engineering information on the fractures themselves.

The potentially toxic substances in fracturing fluids have raised alarms in the environmental community and forced regulators to re-evaluate the balance between public safety and private commercial interests (Centner 2013). FracFocus has been an important avenue for release of information about additives to fracturing fluid. States participating in the registry have established slightly different requirements for disclosure.[5] Recently, producers and contractors have relented somewhat on protection of their formulas, perhaps as a concession to political opposition to oil and gas development. However, recent innovations may have moved away from fluid chemistry, relaxing the perceived value of maintaining confidentiality. The lack of empirical evidence that the fluid additives cause environmental damage suggests that technological

[5] See Wiseman (2013) for background on the debate about trade secrecy, including perceptions of the advantages of public versus private disclosure.

changes rather than increasingly intensive political opposition are the motive, and the results of this study support that interpretation.

The empirical results provide evidence that operators and contractors are learning through experience and collaboration, as shown by production gains in some operator-contractor pairs. The undisclosed additives in injected fluids are not highly productive on average; relatively less productive wells were associated with fluids containing a greater share of undisclosed additives. Trade secret provisions are associated with increased production for some firms, mostly operators rather than contractors, though there are substantial differences between operators. However, because the choice of withholding information about additives is not observed except as an outcome, the estimates in this study should be interpreted cautiously. The analysis cannot determine, for example, whether an operator or a contractor insisted on the trade secret protection for a particular additive used on a particular well.

Operators and contractors recognize that fracking is constantly evolving. Oil and gas companies regularly analyze the productivity of their investments, but those analyses are focused on forecasting the outcome of the next well. Meanwhile, concerns about the environmental costs of fracking specifically and of expanded development more generally have spurred calls for additional regulation. As policymakers consider future regulatory alternatives, identification of the role of experience and the firms that benefit from it and an analysis of disclosure requirements will be valuable.

Background

Fracturing has been used in a variety of forms since the late 1940s as a way to enhance the ability of oil and gas to move through the reservoir rock.[6] An important difference in modern applications is that fewer naturally transmissive reservoirs remain, so wells are drilled into "tighter" geologic formations that make extraction more difficult. Fracturing has thus become essential rather than merely enhancing. The practice of fracturing source rocks began in the 1990s and is widely credited to Mitchell Energy in the Barnett Shale in Texas (Yergin 2011, Zuckerman 2013). However, numerous other operators experimented and contributed technical advances. Methods of completing the wells have evolved and continue to advance. Completion practices are tailored to the geologic characteristics of the formations, fields, and regions, and adjustment of the fluid chemistry is an important margin of production.

Wells are hydraulically fractured after they are drilled.[7] Drilling can be vertical but more often is directional or horizontal. After the drilling rig is removed from the site, frac materials and pumping equipment are brought in. A water-based slurry is mixed at the surface and then pumped down the wellbore and into the target area, which is isolated to focus the high pressure on oil- and gas-bearing rocks and create fractures (Energy and Environmental Research Center 2014). Once initial fractures are created, small grains of sand (or synthetic or ceramic materials) known as proppant are added to the slurry. Pressure pushes the grains into the fractures; as the pressure is released, the material holds the

[6] For an early technical discussion of hydraulic fracturing, see Clark (1949).

[7] A nontechnical synopsis can be found in Kurth et al. (2012), which also provides references to documents offering greater technical detail.

fractures open and creates a permeable pathway for oil and gas to the wellbore. Pressure pumping can be repeated to treat different portions of the wellbore.

Fracturing involves many variables: the amount of fluid and proppant, the amount of pressure, the timing of each stage of the process, and the amounts and combinations of the numerous additives used to reduce friction, alter the fluid viscosity, and improve flow of the well.[8] Characteristics of the injected ingredients, such as whether natural sand or a ceramic substitute is used as proppant, are important considerations for engineers who design and implement fractures.

The fluid chemistry (in the form of additives injected) is an important margin on which contractors can compete. Each additive has a specific purpose in implementing a successful frac and increasing production. For example, high viscosity is desirable as fluid is pumped into the well because it allows more proppant to be suspended in a given amount of fluid. However, reducing friction is also important; that allows more fluid to be pumped by a given amount of horsepower. Other common additives reduce the viscosity later in the process to allow faster recovery of the pumped fluid, kill naturally occurring bacteria that can reduce flow in the well, and help balance the chemistry of the fluid in the reservoir. The recipes—particular combinations of additives—are important proprietary assets for operators and service companies that sell their expertise. When ingredients are proprietary additives, the companies are often afforded nondisclosure rights to protect trade secrets. The FracFocus database identifies additives that are not disclosed.

Considerable research effort has been devoted to technological changes in oil and gas extraction, mostly directed at total factor productivity rather than the marginal productivity of one input. Cuddington and Moss (2000) found that, although the average finding cost of new reserves increased over time, technological adoption reduced the cost that was actually incurred. Chermak and Patrick (1995) focused on the role played by information technology improvements in the cost of extraction of natural gas and found significant benefits from better information. One of the mechanisms for the improvement identified by the authors is greater efficiency in well completion. Adoption of fracking fits both sets of results.

Every shale formation requires some learning on the part of operators as they adapt to specific geological conditions. This study examines a single geologic basin (in contrast to Chermak, Crafton, and Patrick (2012)) and therefore identifies effects of experience that are pertinent only to the Bakken formation. It is similar to previous studies of wartime shipbuilding by Thornton and Thompson (2001) and of oil and gas drilling by Kellogg (2011).

The first modern fracturing activity in the Williston Basin was in the early 2000s in the Elm Coulee field, which is located northwest of Sidney, Montana. There were at least two previous waves of exploration in the basin that never achieved widespread production because perforated vertical wells drilled in the relatively thin layers of shale did not produce enough oil (Energy and Environmental Research Center 2014). The success of the first experiments with fracture stimulation led engineers to seek greater control over propagation of the fractures, primarily by increasing the number of stages and concentrating the pressure on isolated sections of the wellbore. Successes also prompted

[8] Economides and Nolte (1987) is a widely used reference for the technical aspects of hydraulic fracturing.

geologists to consider what was known about the characteristics of the shales, and that knowledge led exploration further east into North Dakota.

Regulation of fracking has been a contentious issue, particularly with respect to shale resources (Merrill and Schizer 2013, Kurth et al. 2012). Debate has proliferated at federal, state, and local levels. The primary authority for oil and gas regulation rests with the states. Regulations are implemented by state-level appointed commissions that are members of the Interstate Oil and Gas Commission Compact. Most states have accommodated and embraced fracking within their borders. In December 2014, New York formalized an impromptu ban that had been in place since 2008. Citing concerns about unknown but potentially harmful impacts, the state joined Vermont, the only other state to ban fracking. Vermont's ban is largely symbolic but western New York has potentially valuable shale resources.

Federal regulations apply to federally owned minerals, which are predominant in some western states, including North Dakota and Montana. The Bureau of Land Management oversees development of federal onshore oil and gas, and in March 2015 it released new regulations for federal lands. Other federal oversight does not apply, including by EPA under the Safe Drinking Water Act.[9] Local actions along the lines of zoning regulations have been pressed in several regions, notably California, Colorado, New York, and, recently, Texas. The legality of those regulations is being challenged, and Colorado's state supreme court recently ruled in favor of state primacy over local authority. Similarly, local bans in Texas were overruled by a state law preventing such action in May 2015. Concern about fracking in particular and development in general makes additional regulation likely.

Conceptual and Econometric Model

Many factors affect well production, including the amount of resource in place before extraction begins. Endowments vary in space but not over time. The physical characteristics of the well and the completion are chosen by operators, sometimes in conjunction with contractors in the case of the frac design. These choices are likely to affect production, and some of the learning and development in methods that occurs comes from varying the inputs employed. Operator and contractor experience with fracturing is a third factor. In addition, unobservable attributes of the well and the formation drilled can be critical to the success of the investment. Important characteristics of the frac job are also unobserved; two examples are the timing of applications of pressure to the wellbore and how fluid additives are physically mixed.

Resource richness is an obvious critical concern for extracting firms, particularly as they jockey for position in fields and seek "sweet spots." Differences of opinion about the relative richness of an area are common prior to drilling. The econometrician cannot observe the distribution of *ex ante* expectations, only the decisions made about which wells to drill and the wells' resulting production. Consideration of spatial correlations between wells is one potential remedy, but parametrically accounting for the unknown

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[9] In the case of the Safe Drinking Water Act, the "Halliburton loophole" provided by the Energy Policy Act of 2005 excludes oil and gas wells from oversight provided for other potential sources of ground water contamination.

form of spatial correlation using a spatial lag or spatial error framework is a complicated task.

A relatively simple parametric control is well-specific fixed effects. These were included in the exploratory specification for this study. However, because the key experience variables of interest do not vary over time, inclusion of those fixed effects would prevent assessment of time-invariant well-specific factors. An alternative strategy is to control for well location. The data set provides latitude and longitude coordinates for each well, which do not change over time. These variables are substituted as a control for changes in production due to location.

For a single well, the fracturing job is fixed in terms of both technical and experiential attributes. Fixed factors include the knowledge and experience (at the time the well is completed) of the operators and contractors and the physical characteristics of the well, such as location and depth. The characteristics of the completion, such as perforations and the frac job, do not vary over the life of the well. Thus, there may be three types of time-invariant factors that are important to consider: (i) time-invariant operator or contractor-specific factors; (ii) characteristics of well completion, such as the engineering details of the fracturing job; and (iii) the (measurable) degree of participants' prior experience when the well is completed. After controlling for physical characteristics, dynamic factors, and the amount of resource in place, the issues of experience and experimentation remain.

Well production is a function of both drilling and completion decisions and of the inherent richness of oil and gas deposits at the location. It is intuitively appealing to presume that prospects are drilled in decreasing order of resource rents (Kemp and Van Long 1980). In that case, positive learning effects from better drilling and completion practices could be offset by decreasing resource richness. Fortunately, the strict ordering result has been shown to deteriorate in both general equilibrium (Amigues et al. 1998) and partial equilibrium with limited extraction capacity (Holland 2003). Capacity constraints appear to be an important issue in the Bakken, and alternative investment opportunities are available to almost all of the firms that are active in the region. Strict ordering of extraction from the richest to the poorest potential resource would downward-bias assessments of learning. Weak ordering of extraction would more accurately assess learning because site selection (by the operator) is implicitly included. The richness of the initial resource in place is not observed so the estimates generated in this study are interpreted as lower bounds.[10] Controlling for the effect of location as a measure of resource richness will account for a substantial share of differentials in production of individual wells.

The empirical analysis of well performance uses a well-month panel of observations, and the dependent variable is the natural logarithm of daily oil production. Because some wells produce for only part of a month, monthly production is converted to a mean across the days the well produced. The logarithm accounts for skewness in the production distribution and facilitates inference.

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[10] Excluding wells that were drilled previously and later recompleted by fracturing may exclude resources that were, at least initially, perceived as the most profitable. However, technological advances could change the rank order of prospective wells so that locations of previously drilled wells may not represent the most profitable locations later or the existing wells may not be optimal.

The econometric specification can be expressed as

$$(1) \qquad \ln(y_{it}) = \alpha \ln(Age_{it}) + \beta' \mathbf{x}_i + \gamma' \mathbf{f}(Exp_{it}) + \lambda' \mathbf{g}(Location_i) + \varepsilon_{it}.$$

Age (of the well) is the number of producing months and is first included as a continuous variable, allowing interpretation of α as a lifetime average decline rate. Well-specific attributes, including elements of the fracturing job, are included in $\mathbf{x}_i$. An important element of this vector is the measure of undisclosed additives. It might seem intuitive to include a vector ($\mathbf{z}_t$) of time-varying attributes that are associated with all of the wells, such as oil and natural gas prices, but the sensitivity of producing wells to price fluctuations is limited.[11]

Consider $\mathbf{f}(Exp_{it})$. Young (2009) explained that learning curves can take any number of shapes. Note that the relationship between experience and production could represent learning across all shale formations or be specific to the Bakken shale. To maintain flexibility in how experience affects production, a third-order polynomial is estimated for the experience measures and compared to a logarithmic form. The locus of experiential gains is not clear (e.g., within operators, within operator-contractor pairs, or through a general diffusion) so they are tested against a null hypothesis of no effect.

The $\mathbf{g}(Location_i)$ term is intended to control for differences in the endowment of oil and gas. Figure 1 depicts variation in average well productivity for the sample region across latitude and longitude coordinates using a Lowess smoother.[12] To account for the nonlinear effect of location apparent in Figure 1, $\mathbf{g}(Location_i)$ is estimated as a flexible polynomial in latitude and longitude that is additively separable in latitude and longitude and takes the form of

$$(2) \qquad \mathbf{g}(Location_i) = Lat_i^{b_1} + Lat_i^{b_2} + Lat_i^{b_3} + Lon_i^{b_4} + Lon_i^{b_5} + Lon_i^{b_6}$$

where $b_i = \{-2, -1, -0.5, 0, 0.5, 1, 2, 3\}$. The λ vector in equation 1 is therefore interpreted as the coefficients on the terms in equation 2. The latitudes are rescaled to be calculated relative to 48.023 north, which is the maximum in Figure 1. Longitude is not rescaled because of its monotonic relationship with average production. An alternative specification of $\mathbf{g}(Location_i)$ is a fixed effect for bins defined by latitude and longitude coordinates, which would create an approximately rectangular grid and allow average production to vary in each bin. Three bin sizes are tested.

A simpler specification than the one in equation 1 includes only well age as a determinant of production and would suggest that geophysical factors strictly determine oil production. Well fixed effects prevent identification of any time-invariant well attribute, including location.

In this framework, it is useful to think about two wells drilled sequentially. The wells are near one another and have the same physical characteristics and operator and contractor, but one well produces more oil than the other

[11] Anderson, Kellogg, and Salant (2014) in recent work in economics demonstrated that geophysical factors generally are prohibitively costly to alter, resulting in price sensitivity when the wells are drilled but not when production commences.

[12] The estimates minimize a tricubic kernel with bandwidth of $1.06\sigma N^{\frac{1}{5}}$ (Silverman 1986). The primary bandwidths are 2.2 for latitude and 3.2 for longitude, which correspond to smoothing over wells within about 60 miles. The effect of the smoothing of the raw data is shown in Figure A1 in an appendix available from the author. Figures 1 and A1 show the same smoothed values, but in Figure 1 the vertical axis is rescaled to smoothed values only to show variation across space while Figure A1 captures the variance in well productivity that requires smoothing.

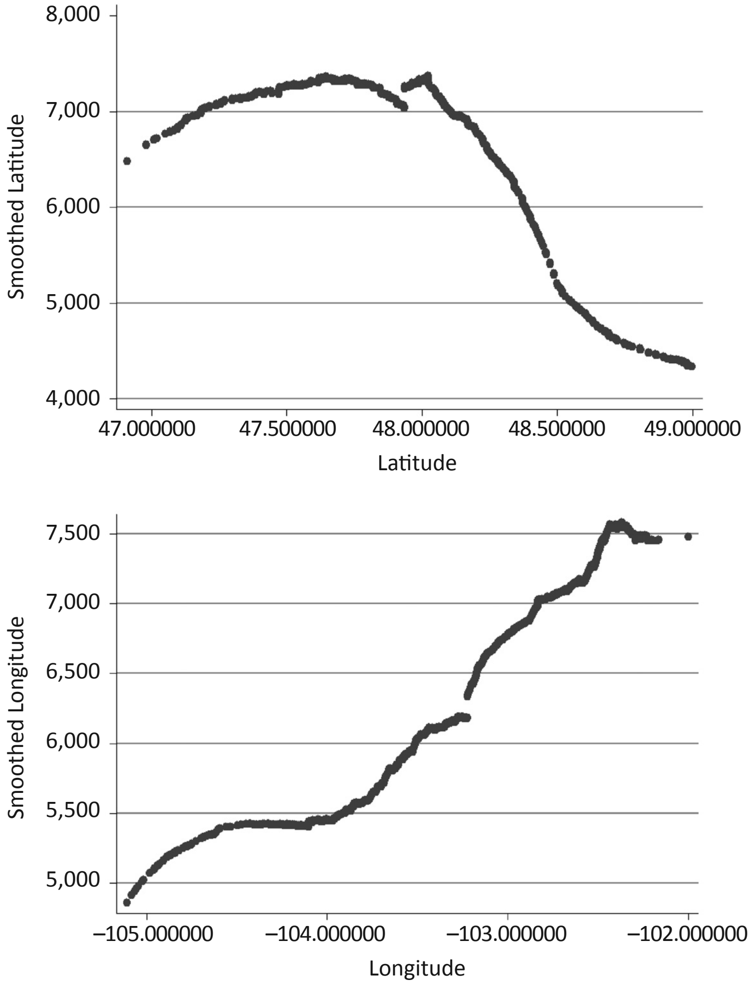

Figure 1. Kernel Smoothed Production by Location

does. If the less productive well is drilled first, the framework will identify positive experiential learning. If the second well produces more oil because one additional fluid additive was injected and that additive was not disclosed in FracFocus, the framework will identify positive returns to additional additives and secret ingredients. Therefore, the structure of ε_{it} is important. The standard errors are clustered at the well level to account for idiosyncrasies in well-level production profiles (discussed further in the next section).

Data

This study uses data on well completions reported to FracFocus by operators. The scope of the analysis is limited to the Bakken region and, in particular, to the nine counties highlighted in Figure 2. Gaswirth et al. (2013) assessed variations in resource deposits across the study area and found that unconventional oil deposits extended west across the Montana / North Dakota border. The sample counties are highly productive—among producing counties in 2011, two of

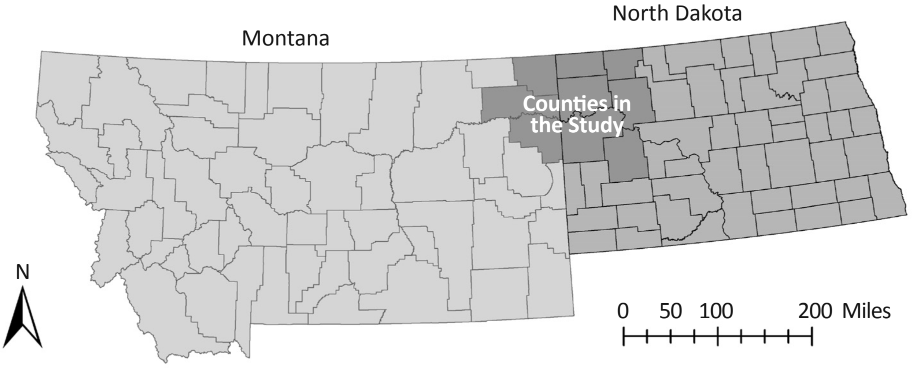

Figure 2. Counties Included in the Analysis

the nine in the sample were in the top 10 in terms of production, five were in the top 25, and all were in the top 200. Limiting the analysis to these counties reduces the sample to 3,679 wells and 3,811 completion records with at most three reported fracturing jobs for a single well. Most of the wells (3,368) are in North Dakota.[13]

Well completions were matched to production data provided by the Montana Board of Oil and Gas Conservation and the oil and gas division of the North Dakota Industrial Commission. Despite unique well-specific identifiers, a small number of the reported wells did not match the production records so the matched sample consists of 287 wells in Montana and 3,195 wells in North Dakota. The sample used for estimation is limited to production months following the fracturing job. And because of the reporting requirements and time scale of the production data, a window of one month on either side of the reported date of fracturing is treated as a coincident with completion. However, because some old wells are recompleted by fracturing, wells that had already been producing are treated and included in the data. Multiple completions of the same well are excluded, again because of concern that the decision to complete the well multiple times could be a result of earlier production outcomes. Wells that were fracked but did not immediately produce are excluded to avoid confounds due to unobserved factors that delayed production. The wells in the analysis were completed between January 1, 2011, and September 30, 2013.

Table 1 briefly summarizes the wells in the sample and reports the number of distinct operators and contractors in each state. The operator is the decision-maker of record for a well. A variety of firms can operate wells, ranging from small operations with one or a few wells to multibillion-dollar public corporations that have thousands of wells (see Table B1 in Appendix B, which is available from the author). A second important type of firm is the fracturing contractor (also called a service company). The number of contractors (listed in Table B2) in Montana and in North Dakota is similar and reflects considerable entry since the 2003 EPA memo when three firms dominated the market. The

[13] Because some wells are not included in the usable data, the estimates presented are attenuated toward zero.

Table 1. Summary of Sample Observations

	Montana	North Dakota	Total
Total			
Wells	311	3,368	3,679
Fracturing jobs	321	3,489	3,811
Producing			
Wells	287	3,195	3,482
Operators	21	47	53
Contractors	11	13	14
Pairings	46	151	161

Notes: The data were reported by operators of wells and collected from FracFocus in September 2013. The sample was limited to wells in nine counties overlying the Bakken Shale as defined in Gaswirth et al. (2013), which are depicted in Figure 2: Burke, Divide, Dunn, McKenzie, Mountrail, and Williams in North Dakota and Richland, Roosevelt, and Sheridan in Montana.

declining concentration in servicing is itself a measure of diffusion—observing entry into well servicing might lead one to expect lower average productivity gains attributable to contractors.

Numerous potential partners are available to operators for any given well, and by choosing the right partner or developing proficiency within a relationship, operators can improve their productivity. Although only one pairing is possible for a given well, an operator can experiment with different partners by drilling multiple wells. The mean number of pairings observed per operator is greater than two in Montana and greater than three in North Dakota. Contractors can compete on price and actively market to operators, which will increase the number of pairings. The drilling boom has imposed constraints on the availability of equipment during the period examined, limiting operators' choices.[14] A third explanation is that operators and contractors are integral partners and there are opportunities for capturing diffusion by employing multiple contractors as part of a drilling campaign. The most common pairings are listed in Table B3.

Using the total number of wells per pair as a proxy for total experience gained, the distribution of experience offers additional insights into both firms' productivity and environmental risk. Table B4 (in Appendix B) reports the aggregate number of wells completed by operator-contractor pairs and their levels of specific experience. Not surprisingly, the eight pairs that had completed more than 100 wells together account for the largest share of the observations. The maximum number of wells observed per pair is 157.

Well production is important to revenue generation and cash flow. Table 2 reports mean initial daily production and mean average production over the well life with oil and gas reported separately for Montana, North Dakota, and the whole sample. These calculations clearly demonstrate the attractiveness of North Dakota relative to Montana in terms of production. The value of wells as investments is evident from this table: an average North Dakota oil well

[14] If equipment shortages are the primary reason, they could explain much of the entry into the well servicing and pressure pumping sectors. The contractor variable in the model includes only firms that provided a comprehensive completion service. The location of servicing centers within the region could be a factor as well.

producing for twelve months with the oil marketed for $75 per barrel would generate a little more than $6 million in revenue. Associated natural gas could provide additional revenue, though infrastructure constraints could limit the ability to sell the gas.

The FracFocus data repository provides technical information on fracturing jobs in both states. Well reports list the additives included in the injected fluid with Chemical Abstract Service (CAS) numbers to identify each ingredient and the proportion of each additive in the final injected fluid. While this information is not precise enough to replicate the exact formula used, it provides sufficient information for assessing the key ingredients in the recipe. The FracFocus records clearly list proprietary additives but omit the CAS numbers.

Because the structural form of the fracking production function is not known and the number of possible ingredients included in various formulas far exceeds the dimensions of available data, the reduced-form empirics must be focused

Table 2. Production Statistics

Measure	Montana	North Dakota	Total
Mean Initial Production			
Oil (billion barrels per day)	265.8 (237.1)	585.3 (469.3)	559.7 (463.3)
Gas (thousand cubic feet per day)	160.0 (250.9)	517.0 (600.0)	488.4 (587.9)
Mean Monthly Production			
Oil (billion barrels)	3,048 (2,207)	6,762 (4,264)	6,426 (4,256)
Gas (thousand cubic feet)	1,250 (1,629)	7,164 (5,856)	6,259 (5,830)

Notes: Mean initial production is the mean daily flow from the first reported production month regardless of how many days were reported. The flows are normalized by different numbers of days. Mean monthly production is calculated across well lifetimes of differing lengths.

Table 3. Completion Description Statistics

Variable	Mean	Standard Deviation	N
Water volume (gallons)	2,343,903	1,563,735	2,809
Proppant/water ratio	10.463	212.407	3,414
Number of additives (count)	35.751	13.245	3,482
Trade secret proportion	0.128	0.122	3,482

Notes: The data were reported by operators of wells and collected from FracFocus in September 2013. The sample was limited to wells in nine counties overlying the Bakken Shale as defined in Gaswirth et al. (2013), which are depicted in Figure 2: Burke, Divide, Dunn, McKenzie, Mountrail, and Williams in North Dakota and Richland, Roosevelt, and Sheridan in Montana. The statistics are calculated from reports to FracFocus. The proppant/water ratio is calculated as the total mass of proppant divided by total mass of water. The number of additives includes all reported ingredients, including water and proppant. Undisclosed additives are each weighted equally and divided by the total number of injected materials to determine the proportion of additives with trade secret protection.

on a handful of statistics. FracFocus does not include detailed engineering data such as pressures used for fracturing, the duration of those pressures, the expected fracture propagation, or results of microseismic surveys. The total volume of water used as a base for the slurry is reported.

The total masses of water and proppant injected can be used to create a ratio that captures how much proppant per unit of water is injected. A greater amount of proppant can better hold open fractures and increase production but also requires a higher fluid viscosity, more advanced breakers to reduce viscosity for flowback, and greater pumping power, all else being equal. The complexity of the injected fluid can be captured by the total number of components in it—additives, water, and proppant. Finally, the model uses a calculation of the proportion of total ingredients in the fluid that are not identified by CAS numbers. These statistics were chosen in part because they represent likely contributors to well productivity, but also because of their potential as environmental risks and likelihood of being subjects of regulation.

Table 3 presents mean values and summary statistics for total water injected, the proppant/water ratio, the number of additives in the slurries, and the proportion of undisclosed additives. The large volumes of water used for fracturing have raised concern about local water supplies and the potential for fracturing to displace other water uses. The amount of water injected is small relative to statewide irrigation withdrawals, though only a subset of all wells in the state are covered in the reports.[15] While the total volume injected in the nine Bakken counties examined is small relative to statewide irrigation applications, the local effects of new demands for water are not known. More detailed data are needed to assess possible local shortages.

Results

Before delving into the main specifications, consider a simplified version of equation 1 that focuses on well dynamics and the effectiveness of locational controls:

$$\ln(y_{it}) = \alpha \ln(Age_{it}) + \lambda' \mathbf{g}(Location_i) + \varepsilon_{it} \tag{3}$$

where $\mathbf{g}(Location_i)$ is first omitted, then included as a well fixed effect, and then included as a locational control by polynomial or fixed effect. The results are reported in Table 4. In the first column, the logarithm of average daily oil production is regressed on a constant and the age of the well. The estimated decline rate (change in production over time) is steep but is similar statistically to other estimates from the Bakken such as Covert (2014).[16] In the second column, well-level fixed effects are included to control for all time-invariant factors that affect a single well, including its location and construction, static price differentials, and fracturing characteristics. The well fixed effects improve the explanatory power of the model and do not significantly change the estimated average rate of decline. However, fixed effects also crowd out many

[15] The greatest value was in North Dakota in 2011; about 10,634 acre-feet (4.7 percent of statewide irrigation withdrawals in 2008) were injected. Note that this exceeds the 1 percent found by Nicot and Scanlon (2012) for shale formations in Texas.

[16] Additional results for hyperbolic and piecewise declines are available on request. Those specifications had no significant impact on the results for undisclosed additives and experiential effects.

Table 4. Logarithm of Daily Average Oil Production: Exploratory Specifications

	1 Constant Plus Age of Well	2 Well Fixed Effects	3 Location Fixed Effects	4 Polynomial Location Control
Well fixed effects	No	Yes	No	No
Location controls	None	None	Fixed Effect	Polynomials
Log production month	–0.490*** (0.00791)	–0.483*** (0.00610)	–0.498*** (0.00748)	–0.495*** (0.00732)
Constant	6.007*** (0.0185)	5.995*** (0.0122)	— —	6.017*** (0.0160)
Observations	34,510	34,510	34,510	34,510
R-squared	0.247	0.719	0.343	0.378
Root mean square error	0.737	0.465	0.689	0.670
Number of clusters	2,253	2,253	2,253	2,253

Notes: The dependent variable is the log of oil produced per production day. Robust standard errors for the well-level clusters are presented in parentheses. The locational polynomial control contains a constant term so the regression constant is omitted. *** $p < 0.01$; ** $p < 0.05$; and * $p < 0.1$.

Table 5. Logarithm of Daily Average Oil Production: Baseline Results

	Learning Effects		
	None	Polynomial	Logarithmic
Log production month	–0.479*** (0.00703)	–0.473*** (0.00640)	–0.474*** (0.00668)
Constant	5.811*** (0.148)	5.786*** (0.152)	5.927*** (0.156)
Total vertical depth	–8.54e-06 (1.37e-05)	–8.28e-06 (1.30e-05)	–6.66e-06 (1.23e-05)
Number of ingredients	0.000495 (0.000961)	–0.000174 (0.00108)	–0.000439 (0.00101)
Proppant/water ratio	6.43e-05*** (1.56e-05)	8.44e-05*** (1.93e-05)	7.47e-05*** (1.78e-05)
Water volume (million gallons)	0.121*** (0.0104)	0.134*** (0.0117)	0.132*** (0.0113)
Proportion of secret additives	–0.197** (0.0897)	–0.176* (0.0917)	–0.179** (0.0869)
Observations	34,510	34,510	34,510
R-squared	0.414	0.422	0.421
Root mean square error	0.651	0.646	0.647
Number of clusters	2,253	2,253	2,253

Notes: The locational controls are fixed effects as in column 4 of Table 4. Robust standard errors for the well-level clusters are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; and * $p < 0.1$.

other potentially interesting variables. The third column replaces well fixed effects with geographic fixed effects in which the region is divided into a grid of one-half of a degree of both latitude and longitude—each rectangle is included as its own fixed effect. Again, the specification has little effect on the estimated rate of decline but it accounts for much of the variation in well performance across space.[17] In the fourth column of Table 4, the well fixed effects are replaced with flexible polynomials in location as described in equation 2.[18]

It appears that the locational variables primarily account for the differences in initial rates of production rather than for the rates of decline in production. In that respect, the variables seem to serve their intended purpose. If location explained all of the differences in the production profiles, there would be little reason to examine completions or the possibility of operators and contractors learning from experience and experimentation. Clustering standard errors at the operator level rather than the well level slightly increases the magnitude of the standard errors but does not affect statistical inference of any of the variables.

Table 5 presents the results of three baseline regressions of the logarithm of oil produced per production day as specified in equation 1 (no learning effects, polynomial learning effects, and logarithmic learning effects). These baseline estimates control for differences in geological potential due to the location of the well using the locational fixed effects previously discussed. The average rates of decline are statistically similar to the ones from the regression with well fixed effects. Measureable dimensions of the fracturing job are also included in the baseline specifications. Higher ratios of proppant to water are associated with greater production rates, as are larger volumes of injected water. This suggests that "bigger" fracs, in the sense of having relatively large amounts of water and proppant, produce more oil. It is not clear, however, that these larger jobs are more profitable because the data include no measures of the costs of inputs. More importantly, the average effect of increasing the proportion of undisclosed ingredients is a *decrease* in average daily production rather than an increase.

To understand this effect, additional specifications like the ones shown in Table 5 were estimated; the deciles of the undisclosed ingredients were replaced with a series of categorical variables. First, a single dummy variable was used that was coded as 1 if any undisclosed additives were used. The estimated coefficient on that variable was negative but not significantly different from zero. Then a series of categorical variables representing four deciles of the proportion of undisclosed additives (10, 20, 30, and 40 percent) were substituted, with the omitted category being full disclosure (zero trade secrets). The results are depicted in Figure 3. The wells that were fractured using the largest proportion of undisclosed additives (greater than 40 percent) have unambiguously lower production. A slightly smaller share of such additives has a positive impact when all other variables are held constant. The

[17] This specification was compared to ones in which a full degree and one-tenth of a degree of both latitude and longitude were used to form a grid and determine fixed effects. There are 29 locational fixed effects in the reported model, 12 when the coarser grid is used, and more than 2,000 when the finer grid is used.

[18] The best fit is achieved with a second-order polynomial in latitude with exponents of –2 and –0.5. The polynomial includes a constant term, which precludes a constant term for the equation when the locational polynomial is included. The optimal polynomial for longitude is third-order with exponents of –2, –0.5, and 0.5.

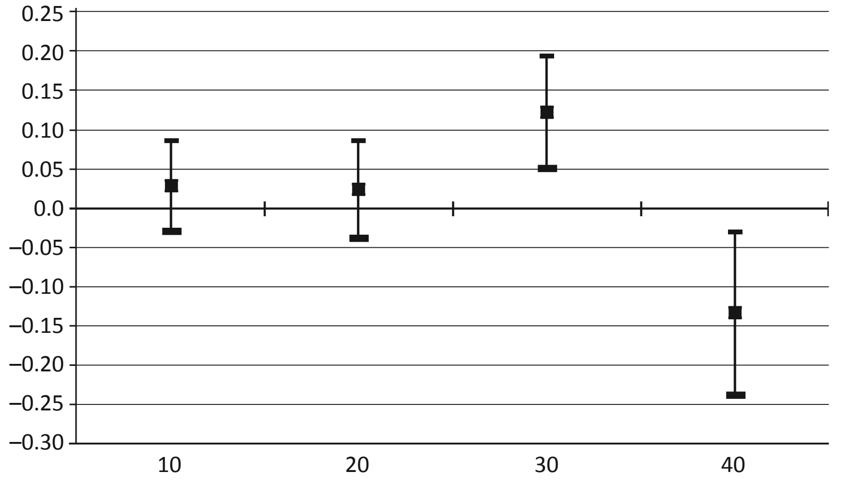

Figure 3. Production Changes across Deciles of Undisclosed Additives

Point estimates and 95 percent confidence intervals from regressions of the logarithm of daily average oil production on categorical variables for the share of undisclosed additives in the fluid. The omitted category is fluids for which all additives were disclosed.

effect of a small proportion of undisclosed additives (less than 20 percent) is not statistically different from disclosing all additives. These results suggest that there is a range within which the undisclosed additives enhanced production (about 14 percent of the observed wells). The approximately 5 percent of wells that were injected with fluid containing the largest proportion of undisclosed additives have relatively low production. One possible explanation is that many of the fracturing jobs that involve a large proportion of undisclosed additives are experimental.

The underlying mechanism that determines whether additives are disclosed is not well specified in the model. If nondisclosure is correlated with high production expectations, perhaps because firms want to keep competitors from recognizing a proprietary formula, the estimates will be biased upward. If, instead, nondisclosure is meant to conceal experiments that may fail, then the estimates will be biased downward. To specify this model fully, additional information is needed to model the firms' *expectations* about production when they report completions to FracFocus.

Next, consider the role of operator and contractor experience in increasing well production. The polynomial and logarithmic specifications reported in Table 5 includes parametric measures of experience along different dimensions. Table 6 reports the results of measures of experience in those regressions. The polynomial regression included third-order polynomial terms for four experience measures: total wells completed, the operator, the contractor, and operator-contractor pairs. This set of experience parameters is jointly significant in all of these specifications. The point estimates of general diffusion effects in the total number of wells completed suggest declining average production, but the parameters are not significant. For operator, contractor, and pairs, the point estimates suggest increasing and concave experience curves. These polynomials indicate that the shapes of the experiential effects for the groups vary.

The logarithmic regression includes the logarithm of experience for each category to allow for positive but decreasing returns to experience. Comparing the polynomial and logarithmic specifications in Table 6 provides some evidence that the logarithmic specification is appropriate in this setting. The results of the

Table 6. Logarithm of Daily Average Oil Production: Parametric Experience Effects

	Learning Effects		
	None	Polynomial	Logarithmic
Well experience		–0.000830 (0.000594)	
Well experience squared		7.75e-07 (1.48e-06)	
Well order cubed		–2.82e-10 (1.09e-09)	
Well experience operator		0.00152* (0.000866)	
Well experience operator squared		–9.17e-07 (5.65e-06)	
Operator order cubed		–1.94e-09 (9.78e-09)	
Well experience contractor		0.00130*** (0.000336)	
Well experience contractor squared		–2.59e-06*** (8.08e-07)	
Contractor order cubed		1.51e-09*** (5.10e-10)	
Well experience pair		0.00127 (0.00136)	
Well experience pair squared		–2.93e-05** (1.47e-05)	
Pair order cubed		9.69e-08** (4.01e-08)	
Log well order			–0.101*** (0.0222)
Log operator order			0.0619*** (0.0141)
Log contractor order			0.0563*** (0.0142)
Log pair order			–0.0142 (0.0121)
Observations	34,510	34,510	34,510
R-squared	0.414	0.422	0.421
Root mean square error	0.651	0.646	0.647
Number of clusters	2,253	2,253	2,253

Notes: The locational controls are fixed effects as in column 4 of Table 4. Robust standard errors for the well-level clusters are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; and * $p < 0.1$.

logarithmic regression are qualitatively similar: well production declines with the total number of wells completed, but both operators and contractors appear to gain useful experience as they complete wells and that experience improves the production of their future wells. There is a slightly larger learning effect for operators and no significant learning effects for operator-contractor pairings.

Clustering by operator increases the standard errors, and the coefficient on the share of undisclosed additives is no longer significant for the specifications presented in Table 5. The experience effects remain jointly significant, but operator learning effects are not individually significant (operator experience effects are jointly significant).

Given the impact of both undisclosed additives and experiential learning, it is natural to consider interactions between them. Those regressions reveal no significant effects of nondisclosure at different points in the learning curve for operators or contractors. Interacting a binary measure of nondisclosure with operator and contractor fixed effects reveals a more subtle story. Undisclosed additives do not increase average production for any contractor. In fact, on average, there are no significantly different average productivities for any contractor with or without undisclosed additives. However, there are differences for operators; in several cases, operators' inclusion of undisclosed additives in the fracturing process is associated with much greater production from the wells. Only one of those operators achieves better than average production when disclosing all of its additives. Therefore, it appears that the option to maintain trade secrets is valuable for a subset of operators.

Table 7 reports additional specifications intended to isolate the effects of maintaining trade secrets. The logarithmic regression reported in the first column is identical to the ones in the third columns in Tables 5 and 6. One way learning could occur is by changing observable inputs—the amount of water and proppant that are injected—and observing the outcome. Such experimentation seems to be occurring in fracturing and is a source of learning for operators. Note that when the controls for the proppant/water ratio and injected volume are dropped (second column), the point estimate on operator learning falls dramatically (relative to the full specification in the first column) and is no longer statistically significant. This is similar to Covert (2014), which found that "larger" fracs were more productive. In addition, the point estimate on undisclosed additives is much closer to zero and is not statistically significant.

The last three columns in Table 7 present the results of including additional fixed effects for operator, contractor, and operator-contractor pairs. Controlling for differences across operators eliminates all learning effects, which suggests that the large differences in production observed in the data are related to operator characteristics rather than to experience gained over time. The experiential gains for operators remain positive but are imprecisely estimated. In contrast, the production differences among contractors are much smaller. Since contractors are not making final decisions about the approach taken to wells and completions (operators do that), this is not especially surprising. It also may help explain why entry into the well servicing sector has been so substantial. A less concentrated sector makes regulatory intervention like the 2003 EPA memorandum less likely in the future. The final column includes fixed effects for operator-contractor pairs, and the results for learning effects are similar to the results in the third column (operator fixed effects).

Table 7. Logarithm of Daily Average Oil Production: Fixed Effects Specifications

			Other Fixed Effects in Addition to Location		
	None	None minus Proppant/Water and Water Vol.	Operator	Contractor	Pairing
Log production month	−0.474*** (0.00668)	−0.483*** (0.00682)	−0.478*** (0.00654)	−0.465*** (0.00722)	−0.469*** (0.00686)
Constant	5.927*** (0.156)	6.007*** (0.173)	5.485*** (0.202)	5.961*** (0.265)	4.260*** (0.272)
Total vertical depth	−6.66e-06 (1.23e-05)	−7.56e-06 (1.35e-05)	1.58e-05 (1.10e-05)	−9.03e-06 (1.18e-05)	2.66e-05** (1.26e-05)
Number of ingredients	−0.000439 (0.00101)	−0.00117 (0.00107)	−0.00111 (0.00121)	−0.00148 (0.00131)	−0.000643 (0.00153)
Proppant/water ratio	7.47e-05*** (1.78e-05)	— —	5.32e-05*** (1.71e-05)	9.76e-05*** (2.15e-05)	8.08e-05*** (2.02e-05)
Water volume (million gallons)	0.132*** (0.0113)	— —	0.130*** (0.0193)	0.171*** (0.0141)	0.160*** (0.0175)
Proportion of secret additives	−0.179** (0.0869)	−0.0772 (0.0916)	0.0515 (0.107)	−0.186 (0.122)	0.129 (0.146)
Log well order	−0.101*** (0.0222)	−0.0224 (0.0240)	−0.0209 (0.0331)	−0.105* (0.0581)	−0.0955 (0.0629)
Log operator order	0.0619*** (0.0141)	0.0123 (0.0142)	0.0279 (0.0239)	0.0440** (0.0172)	0.0338 (0.0481)
Log contractor order	0.0563*** (0.0142)	0.0300** (0.0148)	0.0283 (0.0185)	0.0602 (0.0475)	0.0753 (0.0630)
Log pair order	−0.0142 (0.0121)	0.0216* (0.0127)	−0.0164 (0.0129)	0.00578 (0.0162)	−0.00918 (0.0477)
Observations	34,510	34,510	34,510	30,891	30,891
R-squared	0.421	0.382	0.449	0.420	0.464
Root mean sq. error	0.647	0.668	0.632	0.650	0.626
Number of clusters	2,253	2,253	2,253	2,025	2,025

Notes: The locational controls are fixed effects as in column 4 of Table 4. Robust standard errors for the well-level clusters are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; and * $p < 0.1$.

Table 8 reports learning estimates for the nine largest operators and four largest contractors. Three of those contractors have enjoyed a predominant market position as unconventional resources have grown in importance. The fourth has managed to grow rapidly and achieve a strong position in the Bakken market. Contractor and operator experience has a significant effect on well productivity. The effect of operator-contractor pair experience appears to be increasing and concave but is not significant. The sample of large operators only (defined as operating 100 or more wells) is slightly larger. Many of those companies were active in the Bakken prior to the period examined here. Given earlier results, it is not surprising that large

Table 8. Logarithm of Daily Average Oil Production: Experience Effects by Firm Size

	Large Contractor	Large Operator	Large Contractor and Large Operator
Well experience	−0.000209	−0.00114	−0.000522
	(0.000771)	(0.000811)	(0.00107)
Well experience squared	1.29e-07	1.32e-06	−8.52e-08
	(1.92e-06)	(1.96e-06)	(2.70e-06)
Well order cubed	−2.53e-10	−6.84e-10	1.03e-10
	(1.43e-09)	(1.48e-09)	(2.07e-09)
Well experience operator	0.00191*	−0.00105	0.000321
	(0.00116)	(0.00132)	(0.00180)
Well experience operator squared	−7.44e-06	1.25e-05	1.82e-06
	(6.57e-06)	(8.96e-06)	(1.05e-05)
Operator order cubed	1.19e-08	−1.88e-08	−7.89e-10
	(1.09e-08)	(1.55e-08)	(1.72e-08)
Well experience contractor	0.000942**	0.00167**	0.00191**
	(0.000464)	(0.000653)	(0.000918)
Well experience contractor squared	−2.45e-06**	−3.31e-06**	−4.18e-06**
	(1.17e-06)	(1.29e-06)	(1.80e-06)
Contractor order cubed	1.57e-09**	1.96e-09***	2.49e-09**
	(7.44e-10)	(7.43e-10)	(1.04e-09)
Well experience pair	0.000781	0.00685**	0.00506
	(0.00170)	(0.00321)	(0.00431)
Well experience pair squared	−1.35e-05	−9.44e-05	−6.17e-05
	(1.75e-05)	(6.08e-05)	(7.61e-05)
Pair order cubed	4.73e-08	2.48e-07	1.75e-07
	(4.74e-08)	(2.95e-07)	(3.65e-07)
Observations	22,085	22,275	13,224
R-squared	0.434	0.447	0.472
Root mean square error	0.614	0.630	0.593
Number of clusters	1,371	1,422	804

Notes: The four largest contractors are Baker Hughes, Halliburton, Sanjel, and Schlumberger. Operators of more than 100 wells are Continental, EOG, Hess, Kodiak, Marathon, Oasis, Statoil, Whiting, and XTO. Whiting acquired Kodiak after the time period examined in the data. The locational controls are fixed effects as in column 4 of Table 4. Robust standard errors for the well-level clusters are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; and * $p < 0.1$.

firms have smaller, less significant learning effects. In important ways, the large operators may be more alike than different—firms that have little technical ability to produce oil are less likely to continue investing long enough to become large operators. The third column presents results for the subsample of wells that involved a large operator and a large contractor. In that case, the contractor effects are strengthened. The effects of undisclosed additives in all of the specifications in Table 8 are similar to the effects reported in Table 5.

Discussion

Hydraulic fracturing has revitalized the oil and natural gas industry in the United States. Policymakers at local, state, and federal levels are grappling with how best to regulate oil and gas development in general and hydraulic fracturing in particular. The current regulatory regime focuses on operators. The results of this study suggest that gains from experience with hydraulic fracturing accrue both to the operators, which make decisions about when, where, and how to drill, and the contractors that perform fracturing jobs. This implies that fracking is a moving target for regulators as firms continue to learn and experiment.

Empirical analysis of the effects of undisclosed additives to fracturing fluids on well production reveals that increasing the share of undisclosed additives does not improve well performance on average. Further examination demonstrates that there are important nonlinearities in disclosure—wells fractured with a fluid that contains 30–40 percent undisclosed additives are more productive than wells fractured with a fluid for which all of the additives are disclosed. However, when disclosure of additives exceeds the 30–40 percent threshold, the wells produce relatively less oil. Some operators appear to benefit from the ability to keep the additives secret while others choose always to disclose all of the additives used. This study finds that secrecy itself is not beneficial to contractors on average, at least in terms of well production.

During the period examined (well completions for three years, 2011–2013), the general diffusion of experience with fracking in the Bakken appears to have slowed considerably given estimates from an earlier period in Covert (2014). This study uses a somewhat larger sample because it includes Montana wells. Given the empirical shape of the learning curve, the results suggest that the period of steep increases in productivity has passed and Bakken operators and contractors are now in a period of decreasing experiential returns.

The contractual relationships between operators and contractors are not observed. Kellogg (2011) found large gains in productivity from operator-driller pairs, with gains developing more rapidly under more intimate day-rate contracts. Those productivity gains can partly explain the existence of long-term contracts for drilling rigs. The lack of significant gains in production for operator-contractor pairs suggests that there may be little reason to lock up productive pairs through long-term contracts. Because drilling and completion are sequential options, these findings help explain continued drilling (to preserve productivity gains with particular partners) but delayed completion (where similar productivity gains do not materialize).

Understanding hydraulic fracturing as a process that continues to evolve has important implications for regulation of its environmental impacts. This study represents a first attempt to use FracFocus data for economic estimation. Konschnik, Holden, and Shasteen (2013) identified reasons why the data collected by FracFocus are not sufficient for effective regulatory oversight. This study finds that the data can be useful in estimating learning effects and returns to nondisclosure. However, the coarseness of the FracFocus measures of fracturing jobs may frustrate further attempts to use the data.

FracFocus has been an important avenue by which information about additives to fracturing fluid is released. Participating states vary somewhat in their disclosure requirements. In recent years, the debate about trade secrets has been less heated. Two interpretations are plausible. First, political opponents of oil and gas development have succeeded in imposing local bans on fracturing. An alternative explanation is that innovation in the industry has moved away from fluid chemistry, rendering confidentiality about its formulas less important. The lack of empirical evidence of fluid additives causing environmental damage suggests that companies may have fewer concerns about disclosure.

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