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Title:
Interfirm Learning Economies in Drilling and Environmental Safety*

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ABSTRACT
This paper examines interfirm learning economies in improving productivity and environmental safety in Bakken oil drilling. We distinguish between firms accruing match-specific relationship capital, idiosyncratic match quality, and learning about match quality. We find some evidence that firms do accrue relationship-specific capital which improves firm productivity. However, we do not find evidence that firm or interfirm learning leads to increased environmental safety. We do find evidence that idiosyncratic match quality leads to both higher productivity and improved environmental safety.

JEL **classifications: L51, L71, Q35, Q53**
Keywords: Learning, Shale Oil, Drilling, Environmental Accidents

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1 Introduction

Although there is evidence of learning-by-doing in a variety of industries, the mechanisms that translate experience into productivity gains are not well understood. Much of the existing empirical work has set out to identify and estimate rates of learning economies. As noted by Levitt et al. (2013), the literature is currently seeking to "...move beyond a progress function that simply relates reductions in unit costs to cumulative production." One aspect of learning-by-doing that has received little attention in the literature is interfirm learning, wherein productivity increases result from the joint experience of two firms working together rather than each firm's individual experience.

This paper investigates interfirm learning in improving the productivity and environmental safety of oil and gas operations. Using data on individual wells constructed in the Bakken Shale Play from 2005 to 2014, we apply regression analysis to estimate the effect of interfirm experience on drilling productivity and the number of environmental incidents that occur. Operations in the Bakken are ideal for studying interfirm learning because there are multiple contractors involved in drilling horizontal wells. Companies called "operators" own and design wells and supervise contractors hired for the construction stage. Additionally, the sample period covers the beginning of a boom in horizontal drilling through to a relatively mature drilling process.

Additionally, this paper explores whether interfirm learning leads companies to maintain relationships and reap further productivity gains. Duration analysis is used to show that the likelihood of severing a relationship declines as companies drill more wells together. Although this is consistent with relationship-specific learning, it may also be explained by firms learning about their match quality (Nagypál, 2007).[1] Accordingly, we perform additional statistical tests to strengthen the evidence that it is interfirm learning that influences contracting

[1]In learning about match quality, over time two firms gain information about the underlying productivity of working together; relatively good and more stable matches are maintained, so the likelihood of severing a relationship declines as its duration increases. Nagypál (2007) discusses distinguishing between learning-by-doing and learning about match quality in the context of employer-employee relationships.

choices. This involves estimating how the shared experience of two firms affects the likelihood they continue their relationship in response to a negative oil price shock.

There are three main findings of this work. First, there is some evidence of interfirm learning in improving drilling productivity. Second, there is limited evidence of interfirm learning in improving environmental safety. One obstacle to identification is the potential for endogenous matching among firms. For example, two firms that share similar safety protocols or risk preferences may be more effective at preventing environmental incidents when drilling together and thus more inclined to contract with one another. When controlling for potential endogenous matching, there is no evidence that firms improve their environmental safety as their experience increases. Hence, the characteristics of a pair of two firms working together, not just each firm's own attributes, appear to be important determinants of environmental performance. This may have relevance for companies and policymakers seeking to understand the factors the cause environmental disasters. Third, and finally, firms make contracting decisions that are consistent with interfirm learning. The probability of two companies severing a relationship is shown to decline as their joint experience increases. Moreover, in response to a negative shock, firms are less likely to terminate longer relationships than shorter ones.

There are three primary contributions of this paper. First, it studies interfirm learning in a production process that involves multiple contractors. Kellogg (2011) evaluates learning by two firms (operators and rigs) in drilling vertical wells in Texas and finds evidence of learning that is specific to the operator-rig relationship. In horizontal wells, which are the focus of this paper, operators contract with a rig but also hire another firm (called a directional drilling company) to drill the horizontal section of a well. It is possible to test whether relationship-specific learning occurs between 1) the principal firm and contractors (operator-rig and operator-directional driller), 2) contractors hired by the same principal (rig-directional driller), and 3) all three firms involved in the production process (operator-rig-directional driller). This provides information on which types of interfirm relationships bring about learning economies and may give insights into its mechanisms. Moreover, the results may have relevance for understanding the prevalence of relationship-specific learning in large-scale, complex projects that require collaboration of multiple firms.

Second, while there is extensive literature on learning-by-doing, the relationship between experience and environmental safety has received little attention. Although not evaluating learning-by-doing, Sider (1983) studies the relationship between worker safety and mine productivity and finds that the decrease in productivity of U.S. coal mines in the 1970s was not a result of improved safety conditions. In explaining the effects of firm size on safety violations in natural gas operations, Eyer (2015) finds that an operator's experience, which is included as a control variable, has no effect on the number of violations it receives—this study does not observe well contractors. Interfirm experience may be important for reducing environmental incidents in hazardous industries. The interactions between two firms, in particular the effectiveness of their communication, is thought to play a critical role in preventing environmental disasters. For example, inadequate communication between well operator and contractors has been cited as one contributor to the 2010 Macondo well disaster in the U.S. Gulf of Mexico (Deepwater Horizon Study Group, 2011; National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011).

Third, although the existing literature shows that two firms with a longer history together tend to continue contracting with one another (Kellogg, 2011), this persistence could be explained by firms learning about the underlying productivity their relationship (i.e. learning about match quality). Therefore this paper applies techniques to distinguish between firm behavior driven by learning-by-doing and learning about match quality. This provides more definitive evidence that companies seek to preserve relationship in order to take advantage of the productivity gains that accrue through interfirm learning-by-doing.

There are few studies of interfirm or relationship-specific learning. Huckman and Pisano (2006) investigates how surgeon experience reduces patient mortalities and finds learning associated with a surgeon's experience at a particular hospital, but this learning does not transfer to surgeries carried out by the same surgeon at different facilities. Fitzgerald (2015) analyzes learning in hydraulic fracturing and finds little evidence of productivity gains in oil production resulting from the joint experience of well operators and contractor hired to perform the hydraulic fracturing. There is also literature on learning by employees that is job-specific (Mortensen, 1988; Parsons, 1972), yet it unclear how applicable these results are to interfirm relationships.

Section 2 provides some background information on the Bakken oil play while Section 3 summarizes the data used in this analysis. Section 4 describes the empirical strategies and identification issues and Section 5 presents the results for analyses of interfirm learning. Section 6 provides a brief conceptual framework for learning economies in improving environmental performance and discusses the results of this analysis. Lastly, Section 7 concludes on the findings and opportunities for future work.

2 Background

Drilling in North Dakota is concentrated in the Williston Basin, a hydrocarbon-rich depression spanning 150,000 square miles and stretching into Canada, Montana, and South Dakota (NDGS, n.d.). Nearly all wells drilled in North Dakota target oil in the Bakken and Three Forks formations, which are about 10,000 feet below the surface. Oil deposits have been known for many years, however, the low permeability (i.e. fluids cannot easily flow through the rock) and low porosity (i.e. there is limited void space within the rock) of the area, meant that most of the oil could not be profitably extracted until the recent advances in hydraulic fracturing.

Drilling an oil well involves the well owner, known as the operator. Two contractors employed in drilling that have considerable influence on the speed in which a well is drilled are the drilling contractor and directional drilling company. Drilling contractors supply the rig and crew that operate the rig's equipment and create the wellbore The directional

Table 1: Summary Statistics for Wells

Variable	Obs	Mean	Std. Dev.	Min	Max	P50
Rate (feet/day)	4625	818	303	123	4853	786
Drilling Time (days)	4625	27	11	4	157	24
Measured Depth (feet)	4625	19089	2301	9289	26908	20020
True Vertical Depth (feet)	4625	10213	802	5272	14945	10428
Horizontal Length (feet)	4110	9065	2013	1340	16022	9899
Temperature (°C)	4625	-1	11	-25	18	0
Wind Speed (m/s)	4625	4	1	2	8	4
Experience						
Operator	4625	129	131	1	563	79
Rig	4625	14	12	1	66	11
Directional Co.	4625	339	367	1	1730	206
Operator-Field	4625	25	53	1	329	6
Rig-Field	4625	4	6	1	47	2
Dir. Co.-Field	4625	14	27	1	189	4
Field	4625	45	75	1	424	15
Operator-Rig	4625	11	10	1	65	8
Operator-Dir. Co.	4625	50	65	1	464	26
Dir. Co.-Rig	4625	9	9	1	58	6

Sample includes wells drilled between 2005 and 2014. Experience is measured as the number of wells previously drilled by the respective firm. Operator-rig, operator-directional, and directional-rig experience are the cumulative number of wells drilled by an operator-rig, operator-directional, and directional-rig pairs, respectively.

company drills the horizontal section of a well, although the rig is still involved.

3 Data

Summary statistics for wells in North Dakota are shown in Table 1. There are 4,625 observations in the dataset, which includes horizontal wells that were drilled in North Dakota from 2005 to 2014. The mean amount of time spent drilling a well is 27 days, and the mean length of a well is 19,089 feet. There are 326 drilling rigs, 85 operators, and 48 directional drilling companies in the dataset. Note that for each well, there is an operator, rig, and directional drilling company involved in drilling.

Table 2 summaries the distribution of different interfirm relationships as well as the number of companies drilling within an oilfield. For example, the first row (# of Fields per

Dir. Co.) shows the that the typical directional drilling company is active in 24 different oilfields. That is, the mean number of different oilfields each directional company has drilled a well in is 24. This table highlights that firms usually contract with multiple companies and drill wells in several different fields. The average operator hires seven different rigs and four directional drilling companies. This variation in firm contracting is necessary for identifying the effects of interfirm learning. For instance, if an operator and rig drill wells with only each other, it would not be possible to attribute productivity gains to a particular firm.

Table 2: Summary Statistics for Interfirm Relationships

Variable	Obs	Mean	Std. Dev.	Min	Max	P50
# of Fields per Dir. Co.	48	24.208	41.033	1	176	5
# of Operators per Dir. Co.	48	7.229	10.022	1	42	2.5
# of Rigs per Dir. Co.	48	16.563	29.827	1	130	3
# of Dir. Cos. per Field	327	3.554	2.667	1	13	3
# of Operators per Field	327	2.642	2.019	1	14	2
# of Rigs per Field	327	5.798	6.426	1	44	3
# of Dir. Cos. per Operator	85	4.082	3.626	1	21	3
# of Fields per Operator	85	10.165	13.644	1	84	5
# of Rigs per Operator	85	7.082	8.771	1	45	4
# of Dir. Cos. per Rig	326	2.439	1.48	1	9	2
# of Fields per Rig	326	5.816	4.502	1	20	5
# of Operators per Rig	326	1.847	1.148	1	6	1

This table summarizes the firm-firm pairings and the number of firms operating in different oilfields. For example, the last row, labeled "# of Operators per Rig", shows that among the 326 rigs in the dataset, the mean number of unique operators that a rig worked with was 1.8.

4 Empirical Strategy

This section presents the empirical methods used to estimate interfirm learning economies in well drilling. Section 4.1 details the estimation model for leaning-by-doing in improving the productivity of drilling, and Section 6 describes the model for learning in environmental safety.

4.1 Drilling Productivity

Drilling productivity is measured as the natural log of the total depth of the well (in thousand feet) divided by the days spent drilling (i.e. Ln(feet/day)). Ideally, information on drilling costs or production inputs (e.g. labor-hours) would be observed for each well. However, cost information is limited to indices of average costs of Bakken wells, such as Spears & Associates Drilling & Completion Cost Service (Spears and Associates, 2016), and sparse reporting of information by companies. Detailed data on labor and capital inputs used in drilling are not likely tracked by companies operating in North Dakota and it were, it would not be publicly available.

Despite these data limitations, the rate of drilling likely serves as an accurate proxy for productivity due to the nature of the drilling process. Capital is fixed by the rig, which has certain specifications (e.g. motor size) that determine the speed and depth to which it can drill. Labor use per unit of time is largely set by the long-established positions on a rig (e.g. roughneck, driller, toolpusher, etc.). Thus, productivity improvements are expected to occur by reducing the time required to drill a well rather than reducing inputs required per unit of time spent drilling. Moreover, drilling time is well correlated with costs and input requirements because drilling contractors are typically compensated by operators based on the number of days spent drilling in so called "day-rate" contracts. The speed of drilling is also used in petroleum engineering studies of drilling efficiency (Perry, 1992; Studer, 2007). Lastly, the conventional view of companies involved in drilling oil and gas wells is that drilling time and costs are correlated (Halliburton, 2015).

Equation 1 presents the first learning-by-doing specification. The unit of observation is a well, where each well has an associated operator o, rig r, directional company d, field f, and date t. The dependent variable (LnRate_{ordft}) is the natural log of the well's depth (in thousand feet) divided by the number of days spent drilling.

$$LnRate_{ordft} = \alpha_0 LnE_{ot} + \alpha_1 LnE_{oft} + \alpha_2 LnE_{ft} + \beta \mathbf{x}_{ordft} + \phi_o + \kappa_f + \lambda_t + \epsilon_{ordft} \quad (1)$$

The variable E_{ot} is the experience of operator o within the Bakken and measured as the cumulative number of wells drilled by the operator prior to date t. The variable E_{oft} is the number of wells drilled by operator o in field f, which allows for quantifying learning by the operator within an oilfield. The final experience variable (E_{ft}) measures aggregate experience within a field as the cumulative number of wells drilled by all operators within field f.

The vector $\mathbf{x}_{ordft}$ contains several control variables. These include the well's true vertical depth (TVD), measured depth (MD), average ambient temperature and maximum wind speed during the drilling period, and a variable indicating whether the well was drilled in the Bakken or Three Forks formation. The final control consists of an indicator variable for whether a spud rig was used to start the well divided by the well's MD.[2] The parameters ϕ_o and κ_f are operator and field fixed effects, respectively. The parameter λ_t encompasses a year-quarter fixed effect (2005Q1, 2005Q2, etc.) and month of year fixed effect (January, February, etc.), and the final term (ϵ_{ordft}) is the idiosyncratic error.

Equation 1 includes the experience of only the well operator and omits the experience of the contractors involved. Learning-by-doing studies often do not account for contractor experience (Argote et al., 1990; Benkard, 2000; Irwin and Klenow, 1994), and failing to do so may lead to incorrectly attributing learning to principal firms or concluding that learning does not occur.. Learning associated with rigs may result from crews increasing their proficiency with equipment or improving the management of rig operations. Learning by directional companies may occur as they gain knowledge of geologic formations in field or increase their proficiency with tools and equipment.

In equation 2, rig and directional driller experience variables are included. The variables

[2] Spud rigs are used to drill the first one to two thousand feet of a well. Allowing the effect of using a spud rig to vary with well depth, this variable accounts for the fact that using a spud rig reduces the larger rig's drilling time by a fixed number of days irrespective of its depth.

E_{rt} and E_{dt} are the cumulative number of wells drilled by rig r and directional driller d, respectively, prior to date t. Learning by contractors that is oilfield specific is captured through the variables E_{rft} and E_{dft}, which measure the number of wells previously drilled by rig r and directional driller d in field f, respectively.

$$\begin{aligned} LnRate_{ordft} = \alpha_0 LnE_{ot} + \alpha_1 LnE_{oft} + \alpha_2 LnE_{ft} + \\ \alpha_3 LnE_{rt} + \alpha_4 LnE_{dt} + \alpha_5 LnE_{rft} + \alpha_6 LnE_{dft} + \\ \beta \mathbf{x}_{ordft} + \phi_o + \psi_r + \zeta_d + \kappa_f + \lambda_t + \epsilon_{ordft} \end{aligned} \quad (2)$$

In interfirm learning, productivity gain arise from the shared experience of two (or more) firms. That is, the number of wells drilled by a pair of firms may affect the speed in which they drill future wells. There are four relationships that may give rise to interfirm learning: 1) operator-rig, 2) operator-directional driller, 3) rig-directional driller, and 4) operator-rig-directional driller. Equation 3 includes experience variables for each of these relationships to test for the presence of interfirm learning.

$$\begin{aligned} LnRate_{ordft} = \alpha_0 LnE_{ot} + \alpha_1 LnE_{oft} + \alpha_2 LnE_{ft} + \\ \alpha_3 LnE_{rt} + \alpha_4 LnE_{dt} + \alpha_5 LnE_{rft} + \alpha_6 LnE_{dft} + \\ \alpha_7 LnE_{ort} + \alpha_8 LnE_{odt} + \alpha_9 LnE_{rdt} + \alpha_{10} LnE_{ordt} + \\ \beta \mathbf{x}_{ordft} + \phi_o + \psi_r + \zeta_d + \kappa_f + \lambda_t + \epsilon_{ordft} \end{aligned} \quad (3)$$

The variable E_{ort} is the number of wells operator o and rig r drilled together prior to date t. Similarly, the variables E_{odt} and E_{rdt} are number of wells the drilled by the operator-directional driller and rig-directional driller pairs, respectively. The final experience variable E_{ordt} measures the joint experience of all three firms: operator, rig, and directional driller.

A potential obstacle to identifying interfirm learning is endogenous matching among firms. Firm-specific, time-invariant unobservables that influence drilling productivity are captured in equation 3 by the firm-level fixed effects (ϕ_o, ψ_r, and ζ_d). However, there may be unobservables that are specific to a pair of firms (e.g. an operator and rig). This creates endogeneity if these pair-level unobservables affect drilling productivity and are correlated with the pair's experience (i.e. the number of wells the two firms have drilled together). For example, two firms that share similar characteristics in management style or workflows may be more productive together than two firms that are dissimilar. If companies tend to contract with companies they are more productive with, then these pair-level characteristics may be correlated with the experience of the pair.

Failing to account for endogenous matching among firms may misattribute productivity improvements to interfirm learning rather than the pair-level unobservables. This paper follows the approach by Kellogg (2011) by including specifications with fixed effects for firm pairs to control for pair-level unobservables. Interfirm learning is thus identified through variation in experience within a pair of firms. Put differently, it is assumed that changes in idiosyncratic firm pair traits are due to firms learning about each other.

5 Firm Learning and Productivity

Here we present two distinct analyses of the impact of firm experience on productivity. In the first, we regress a cost measure (drilling speed) on measures of firm and firm-pair experience, with and without firm-pair fixed effects. We find modest evidence that joint operator-rig experience reduces costs when firm-pair fixed effects are included ($p \leq 0.1$). We also find that rig experience reduces costs, but only when firm-pair effects are omitted. Taken jointly, these results suggest that operator-rig learning and unobserved match quality both impact productivity.

In the second analysis, we attempt to distinguish between learning that leads to accrual of firm-pair specific relationship capital (learning to work together more effectively) and learning about the fixed quality of the firm-pair match. We find evidence that operator-rig experience leads to valuable relationship-specific capital.

5.1 Drilling Productivity

Table 3 provides estimation results for equations 1-3. This section gives a detailed description of the full results, but the table suggests one overall finding. That is, there is evidence of interfirm learning, but it is not definitive. In specifications that account for endogenous matching among firms by including firm-pair fixed effects (columns 5 and 6), there is evidence of learning among operators and rigs. Alternatively, in specifications that do not include firm-pair fixed effects, there is evidence of interfirm learning among rigs and directional companies (column 3) but not between operators and rigs (column 4).

The results for equation 1, where only operator experience is included, are shown in column 1 of Table 3. The coefficient estimate for the experience of an operator within a field (LnE_{oft}) is 0.031 and statistically significantly different from zero at the 1% level. When the experience of the contractors are included (column 2), the coefficient estimate for operator experience within a field becomes 0.012 (p=0.227). This highlights that failing to account for the experience of contractors may attribute learning to the principal firm. Indeed, there is evidence of learning by contractors. The coefficient estimates for rig experience (LnE_{rt}) and rig experience within a field (LnE_{rft}) are 0.086 ($p<0.01$) and 0.020 (p=0.083), respectively. There is no evidence for learning by directional drillers, and in fact the coefficient estimate for the experience of the directional driller is -0.037 (p=0.036). This could result if, as directional drillers increase their experience, they are hired for more difficult wells that take longer to drill. Control variables are used to account for factors that may influence the time required to drill a well (depth, geologic formation, and oilfield). However, if these do not fully control for the inherent difficulty of drilling a well, and if directional drillers with greater experience are hired for more time-consuming wells, this may cause the coefficient estimate for experience variable of the directional driller to be negative.

Columns 3 and 4 of Table 3 introduce experience variables for each pair of firms involved in drilling: operator-rig, operator-directional company, and rig-directional company. In column 3, there is evidence of learning specific to the rig and directional driller (i.e. the two contractors) but not the operator-rig pair. The coefficient estimate for joint experience of the rig and directional driller is 0.016 (p=0.081), and the coefficient for operator-rig experience is 0.010 (p=0.473).

As noted in Section 4.1, there is a potential for endogenous matching among firms. There may be unobservables that are specific to a pair of two firms (i.e. an interfirm relationship) that 1) influence the productivity of drilling and 2) are correlated with their joint experience. For example, if two firms are highly compatible in terms of management style or risk preferences, these unobserved factors may increase their joint productivity (two compatible firms drill faster together) and may be correlated with their joint experience (two compatible firms are more likely to drill together).

To deal with this issue, columns 5 and 6 include pair fixed effects for each of the interfirm relationships. In column 5, the coefficient estimate for joint operator-rig experience is 0.046 and nearly significant at the 10% level (p=0.100). In column 6, all experience variables included, the coefficient estimate for the joint operator-rig experience is significant (p=0.064). When including firm-pair fixed effects, the coefficient estimate for the operator-rig experience increases in magnitude, which is counterintuitive. Under endogenous matching, without the pair fixed effect, the coefficient estimate is biased upward and its inclusion should correct the bias to bring the coefficient estimate downward. This would suggest that firms are more likely to drill with companies that they drill more slowly with (negative correlation between unobservables and joint experience). A possible explanation is that particularly good operator-rig matches drill wells which are more challenging from a technical standpoint and which require slower drilling speeds (ie, that match quality is negatively correlated with unobservable geological characteristics, which lead to slower drilling speeds).

Table 3: Regression Results- Interfirm Learning in Drilling Productivity

	(1) No Contractors	(2) Contractors	(3) Firm Pairs	(4) Firm Triad	(5) Firm Pairs FE	(6) Firm Triad FE
Operator	0.025	0.007	-0.002	-0.003	-0.025	-0.026
LnE$_{ot}$	(0.019)	(0.017)	(0.018)	(0.018)	(0.035)	(0.035)
Operator-Field	0.031***	0.012	0.015	0.015	0.006	0.006
LnE$_{oft}$	(0.008)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Field	-0.000	0.010	0.014	0.013	0.004	0.004
LnE$_{ft}$	(0.013)	(0.012)	(0.013)	(0.012)	(0.013)	(0.013)
Rig		0.086***	0.066***	0.062***	0.023	0.018
LnE$_{rt}$		(0.014)	(0.017)	(0.018)	(0.024)	(0.025)
Directional		-0.037**	-0.045**	-0.046**	-0.074***	-0.076**
LnE$_{dt}$		(0.018)	(0.018)	(0.018)	(0.037)	(0.037)
Rig-Field		0.020*	0.016	0.016	0.010	0.010
LnE$_{rft}$		(0.012)	(0.010)	(0.011)	(0.011)	(0.011)
Directional-Field		-0.005	-0.011	-0.011	0.002	0.002
LnE$_{dft}$		(0.008)	(0.008)	(0.008)	(0.010)	(0.010)
Operator-Rig			0.010	0.017	0.046	0.056*
LnE$_{ort}$			(0.014)	(0.017)	(0.028)	(0.030)
Operator-Dir			0.006	0.007	0.015	0.017
LnE$_{odt}$			(0.009)	(0.009)	(0.026)	(0.026)
Rig-Dir			0.016*	0.030	0.037	0.059
LnE$_{rdt}$			(0.009)	(0.021)	(0.026)	(0.054)
Op-Rig-Dir				-0.018		-0.027
LnE$_{ordt}$				(0.024)		(0.052)
Firm X Firm FE	No	No	No	No	Yes	Yes
N	4642	4625	4625	4625	4625	4625

Dependent variable in all specifications is the log rate of drilling a well. Firm, oilfield, and time fixed effects and controls included in all specifications. Standard errors clustered on field in parentheses. Firm fixed effects include operator fixed effects for column 1 and operator, rig, and directional drilling level effects for columns 2-6. Firm X Firm fixed effects are interacted firm-level effects; Column 5 includes operator-rig, operator-directional driller, rig-directional driller FEs. Column 6 includes all interacted effects in column 5 and operator-rig-directional driller level effect. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3 suggest some evidence of interfirm learning but it not conclusive in all specifications. Without including firm pair fixed effects, there is evidence of learning specific to rigs and directional companies (column 3). When including firm pair fixed effects (columns 5 and 6), there is some evidence of interfirm learning among operators and rigs.

While not definitive, these results can provide some insights on interfirm learning. First, interfirm learning appears more likely to occur in relationships where there is more interaction among personnel of the two companies. Operators and rigs likely have significant interactions because the operator's representative on the drill site (referred to as the "company man" or "well site manager") supervises operations. This person has typically worked many different roles on a rig and has extensive experience in drilling (Baker, 2001). Directional drilling companies are hired to use specialized tools to drill the lateral section of a well, and while engaged with the rig crew that is also involved in drilling the well's lateral, there may be less interaction with the operator. This may also explain why there is some evidence of interfirm learning among rigs and directional drillers (column 3) but not operators and directional drillers.

A second insight pertains to the prevalence of relationship-specific learning in production process that involve several firms. There is solid evidence of interfirm learning in vertical wells drilled by two firm (operators and rigs) (Kellogg, 2011), yet learning appears less significant among the three firms involved in drilling horizontal wells. A potential explanation is that the additional complexity and coordination required in operations that involve the specialties of several firms may hinder interfirm learning. Production processes that require three companies may reduce the interaction between any two firms. Instead of vigorous learning among two different firms, there is modest (or no) interfirm learning among all three firms.

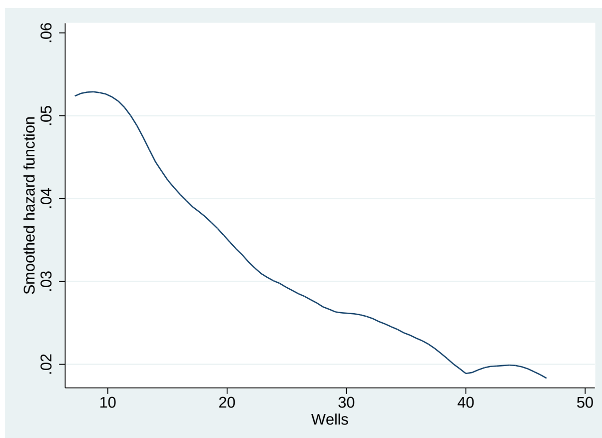
Finally, a number of point estimates shift significantly when firm pair (or triad) effects are included (most notably rig experience and operator-rig joint experience). This provides suggestive evidence of endogenous matching, in which firms match on traits unobserved to the econometrician.

5.2 Contracting Choices

This section presents and alternative test for interfirm learning, which can also distinguish between firms learning how to work together more effectively (accruing relationship-specific capital) and firms learning about the fixed quality of a relationship-specific match. We find evidence that firms do accrue relationship specific capital.

Intuitively, we estimate a hazard function of the likelihood of terminating a relationship between operators and rigs over time.[3] Figure 1 shows the smoothed hazard function estimated by the Cox proportional hazard regression. The hazard function is generally declining as duration of the relationship increases, which means that the rate of failure of an operator-rig relationship is declining as its tenure grows.

Figure 1: Estimated Hazard Function for Operator-Rig Relationships



We see that the hazard function generally slopes downward, which means that as an operator's experience with a rig increases, it is less likely to release the rig. While the results of the duration analysis can be explained by interfirm learning, other factors may cause the downward sloping hazard function. Nagypál (2007) notes that in employer-employee relationships, it can be difficult to distinguish between learning-by-doing and learning about match quality.[4] There may be a similar difficulty for the operator-rig relationship. Learning-by-doing occurs

[3] We estimate a Cox Porportional hazard model. This model has the advantage that it is non-parametric and thus does not force a particular functional form to the data.

[4] There are several articles relating to on the job learning by doing and learning about match quality (Farber, 1993; Flinn, 1986; Jovanovic, 1979; Mortensen, 1988).

as agents gain knowledge that is specific to the employer. In contrast, learning about match quality arises when agents learn about the productivity of the employer-employee pair. In drilling, learning-by-doing may result from rigs and operators increasing their shared experience; learning about match quality may occur as firm gain knowledge about the underlying productivity of their relationship (i.e. how good of a match the two firms are).

A downward-sloping hazard function for a relationship can be explained by learning-by-doing or learning about match quality (Nagypál, 2007). With learning-by-doing, "match-specific capital" grows as the joint experience of two firms increases, and operators are less likely to release rigs they have more experience with because the pair is more productive. For learning about match quality, operators gain knowledge over time about which rigs are a good match. Rigs that are relatively poor matches are released early on, which leaves higher quality matches that are less likely to be released. Hence, the hazard function shown in Figure 1 does not necessarily imply that interfirm learning causes operators and rigs to sustain relationships, since it could be explained by firms learning about match quality.

Nagypál (2007) notes that exogenous shocks can help distinguish learning-by-doing from learning about match quality. Under learning-by-doing, when a negative shock occurs, operators are less likely to release a rig that it has more experience with because the two firms are relatively more productive. That is, there is match-specific capital that has accrued and will be destroyed if the relationship ends. Under learning about match quality, match-specific capital does not necessarily increase as firms drill more wells together, so in response to a negative shock, operators may be willing to terminate the more experienced rigs.[5]

To determine whether learning-by-doing or learning about match quality is driving the duration of operator-rig relationships, we evaluate contracting decisions in response to an exogenous oil price shock that occurred in 2008. We estimate whether a rig's experience

[5] Nagypál (2007) offers an concise summary of this point in the context of employee-employer relationships. Briefly, in learning about match quality, employers become more selective over time and drop low quality matches, which causes match-specific capital to increase with tenure; however, the option value of keeping an employee (and learning more about their match quality) declines over time as more information is acquired, which in turn reduces match-specific capital.

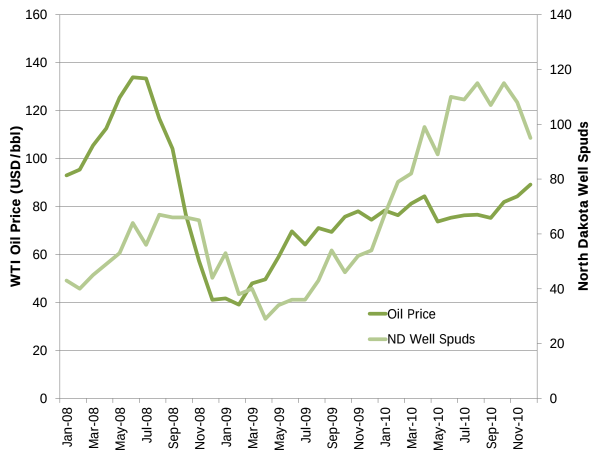
with an operator influenced the likelihood that the rig was retained. If relationship-specific learning-by-doing is occurring, operators should retain rigs that they have drilled more with in the past. Alternatively, if firms are only learning about match quality, a rig's experience with an operator should not influence whether it is released or not.

Oil prices dropped 80% from \$145 per barrel in July 2008 to \$30 per barrel in December 2008 (Figure 2). Prices slowly rebounded in the following years, reaching \$80 per barrel in October 2009 and eventually \$100 per barrel in 2011. Drilling activity in North Dakota fell, although with a lagged response to the price decline. The number of wells spud (i.e. wells that started drilling) in North Dakota peaked in September 2008 at 67, fell by more than 50% to 29 spuds in April 2009, and steadily increased back to 67 by January 2010.

The observations are limited to operator-rig pairs that drilled wells together from October 2006 to September 2008. The shock is assumed to start at the end of September 2008 because that is the month that well drilling peaked in North Dakota; however we run specifications where the sample period is varied. An issue with selecting this time period is that there are fewer operator-rig pairs than in the total dataset. There are only 44 operator-rig pair observed in the dataset that drilled wells between October 2006–September 2008. A rig is considered to be released and a relationship terminated if an operator-rig pair drilled together during October 2006–September 2008 but did not drill in the subsequent two years (October 2008–September 2010). Of the 44 operator-rig relationships, 29 were continued after the shock and 15 were terminated.

The unit of observation is an operator-rig relationship, where an operator and rig drill at least one well together. The duration is measured as the number of wells drilled before the relationship is terminated. A relationship is considered to end if an operator and rig pair do not drill at least one well together for 12 or more months. Defining a relationship as ending if inactive for 12 months allows for some relationships in the sample to have ended—otherwise there would be no failures in the dataset. Furthermore, using 12 months accounts for situations where an operator temporarily releases a rig when they do not have a well to

Figure 2: Oil Prices and Wells Spud in North Dakota



drill, such as if drilling slows down for the winter months, but soon rehires the rig. There are a total of 736 operator-rig relationships observed, and of these 423 are considered to have terminated.[6] The average duration of a relationship is 8.5 wells with a standard deviation of 10.4 and a minimum and maximum of 1 and 68, respectively.

Equation 4 presents a logit model used to estimate the effect of joint operator-rig experience on the probability a relationship is terminated. In this model, that probability that an operator-rig relationship is terminated follows the cumulative logistic function $F(\cdot)$. The variable $RelExp_{or}$ is the relative experience of rig r with operator o; it is calculated as the number of wells rig r has drilled with operator o relative to the rig that has the least experience with operator o. For example, if operator employs two rigs (A and B), and rig A has drilled 4 wells with the operator and rig B has drilled 2 wells with the same operator, then the relative experiences of rigs A and B are 2 and 1, respectively. This allows for estimating how a rig's experience with an operator, relative to all other rigs employed by that operator, affects whether it is retained.

$$Pr(Terminate_{or} = 1) = F(\beta_0 + \beta_1 RelExp_{or}) \tag{4}$$

[6] A relationship is not considered to have ended if the date of the last well drilled by an operator-rig pair was within one year of the end of the sample period (June 2014) or if the well was the last well drilled by the operator.

The results for equation 4 are provided in Table 4 with coefficient estimates, as opposed to exponentiated coefficients. The coefficient estimate for a rig's relative experience with an operator ($RelExp_{or}$) is -0.68 and statistically significantly different from zero at the 5% level. This suggests that an increase in a rig's relative experience with an operator reduces the probability that it is released. Specifically, a one unit increase in its relative experience reduces the probability of being released by about 10% (calculated at the mean). Column 2 shows an alternative specification where operator-rig experience is replaced with a rigs total experience. The coefficient estimate for rig experience is not statistically significant, which demonstrates that a rig's overall experience does not appear to drive termination decisions. Column 3, which includes both operator-rig experience and rig experience, also shows that operators are less likely to terminate rigs that they have accrued greater experience with. Columns 4-6 present the results of an OLS estimation model, and the coefficient estimates are still negative and statistically significant for operator-rig experience. Appendix C presents the estimation results for equation 4 when the sample period is varied. Generally the results remain consistent when varying the time period.

The results in this section demonstrate that in response to negative shocks, companies are less likely to end relatively long relationships. This strengthens the case that learning-by-doing, as opposed to learning about match quality, causes firms to sustain relationships.

6 Environmental Incidents

6.1 Conceptual Framework

This section focuses on a conceptual framework for the effect of experience on environmental incidents. Since safety effort is not observed, it is useful to sketch a model that relates experience and safety effort to environmental incidents. The model will provide information on the direction of the bias from not including safety effort. Assume firms incur a cost for undertaking environmental safety effort (e.g. preventing oil spills). This cost (C) is linear and

Table 4: Logit and OLS Estimation Results for Relationship Termination

	(1) Logit Terminate	(2) Logit Terminate	(3) Logit Terminate	(4) OLS Terminate	(5) OLS Terminate	(6) OLS Terminate
$RelExp_{or}$	-0.68**		-1.06**	-0.04***		-0.09**
	(0.31)		(0.47)	(0.01)		(0.01)
$RelExp_{r}$		-0.11	0.46		-0.02	0.05***
		(0.10)	(0.39)		(0.01)	(0.01)
Constant	0.75	-0.26	0.38	0.48***	0.42***	0.44***
	(0.60)	(0.46)	(0.57)	(0.10)	(0.10)	(0.10)
N	44	44	44	44	44	44

Robust standard errors in parentheses. The variable *Terminate* indicates if an operator-rig relationship ends; the variable is equal to 0/1 for 29/15 of 44 observations.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

strictly increasing in safety effort (z): $C(z) = \gamma z$, where $\gamma > 0$. Environmental incidents are a function of experience (E) and safety effort: $S = S(z, E) = \alpha z^{-1} + \beta E$, where $\alpha > 0$ and $\beta < 0$. Note this function requires the values of α, β, z, and E are sufficiently well-behaved so that S is always non-negative. The implications of modifying this specific functional form are discussed below. Incidents are then strictly decreasing in both safety effort and experience. That is, greater experience reduces environmental incidents for a given level of safety effort. This is consistent with the notion of passive learning that is an "...incidental and costless byproduct of a firm's production activities." (Thompson, 2010).[7] This functional form implies that the marginal effect of safety effort on incidents is independent of the level of experience (i.e. $S_z = -\alpha z^{-2}$).

Firms incur a cost for incidents, which may include clean-up expenses and fines, and this cost is linear in the level of incidents: $h(S) = \delta S$, where $\delta > 0$. Note that this cost may not reflect the full social cost of environmental damages. By substituting in $S(z, E)$ from above, $h(S) = \delta(\alpha z^{-1} + \beta E)$.

There are drilling costs, which are unrelated to safety effort, and defined by the function

[7] Covert (2014) provides evidence that Bakken firms primarily learn passively.

$g(x)$, where x is a vector of production inputs (e.g. labor and capital). For simplicity, the costs of safety, environmental incidents, and other production costs are additively separable. The firm's problem is to choose inputs (x) and safety effort (z) to minimize the cost of drilling a well subject to a production function $F(x)$:

$$\underset{x,z}{\text{minimize}}\ g(x) + C(z) + h(z, E), \quad s.t.\ F(x) = 1$$

The firm's cost minimizing level of environmental safety effort (z^*) is chosen such that

$$C_{z^*} = \gamma = \delta \alpha z^{-2} = -h_{z^*}$$

Hence, firms choose a level of safety effort ($z^* = \alpha^{1/2}\beta^{1/2}\gamma^{-1/2}$) such that the marginal cost of additional effort (C_{z^*}) is equal to the marginal benefit of avoiding incidents ($-h_{z^*}$).

This result shows that, under the assumptions thus far, the level of experience E does not affect the firm's optimal choice of safety effort. An increase in experience clearly reduces environmental incidents since $S_E = \beta < 0$ and z^* is unaffected. This setup motivates an empirical model that estimates the effect of firm experience on environmental spills. In the empirical section, experience is measured as the natural log of the number of wells previously drilled by a firm. This captures the stock of knowledge acquired by a firm as it engages in the production process.

In this setup, there is not expected to be a correlation between experience and safety effort, which is desirable in the empirical estimation because safety effort is unobserved. This is the case because, by assumption, the marginal effect of safety effort on incidents (S_z) is not a function of E. If this assumption was relaxed, the effect of experience on incidents would be more nuanced. An increase in experience has the direct effect of reducing incidents through $S(z, E)$ but also has the indirect effect through altering safety effort. These effects can be seen by taking the derivative of S with respect to E: $\frac{dS}{dE} = \frac{\partial S}{\partial E} + \frac{\partial S}{\partial z^*}\frac{\partial z^*}{\partial E}$. The direct effect ($\frac{\partial S}{\partial E}$) is negative; the sign of second term (the indirect effect) is negative as long as

$\frac{\partial z^*}{\partial E} \geq 0$.[8]

Thus, when allowing for experience to alter the marginal effect of safety effort on incidents ($S_{zE} \neq 0$), the firm's optimal choice of safety effort increases, and there is then a positive correlation between experience and safety effort. The purpose of this model is not to make a case for a particular functional form for the cost of safety and environmental incidents but rather discuss the assumptions necessary for identifying learning in environmental safety given that safety effort in unobserved. The impact of unobserved safety effort on the empirical estimation is discussed below.

Learning may occur through both within-firm and interfirm experience. Firms may increase their knowledge of efficient safety protocols and individuals may become more proficient at preventing accidents. Just as the joint experience of two firms has been shown to affect productivity (Kellogg, 2011), interfirm experience may also influence environmental safety. One potential mechanisms is better communication with other firms engaged in the production process. As noted in Section 1, miscommunication among firms has been cited as a cause of environmental incidents in drilling in the past. The National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, for example, reported that "poor communication" between the well operator and its contractors was a contributing factor to the incident. This has also been noted as in other oilfield accidents and near misses (BSEE, 2013, 2015).

Equation 5 estimates learning economies in environmental safety. The unit of observation is a well drilled, and the dependent variable (Env_{ort}) is the number of environmental incidents that occurred while drilling.

$$Env_{ort} = \alpha_0 LnE_{ot} + \alpha_1 LnE_{rt} + \alpha_2 LnE_{ort} + \beta Days_{ort} + \phi_o + \psi_r + \lambda_t + \epsilon_{ort} \quad (5)$$

[8] To see when $\frac{\partial z^*}{\partial E} \geq 0$, let $C_z \geq 0$ and $h_{zE} \leq 0$; an increase in E causes the RHS of the FOC $C_z = -h_z$ to increase, and the level of safety effort must rise for the LHS to increase and maintain the condition.

Each well has an operator o, rig r, and is drilled at time t. This analysis considers only environmental incidents that occur during drilling and not while a well is in production. Drilling contractors are released once a well has been drilled, and thus it is not possible to study interfirm learning in the production stage.

As in the previous section, the experience of each firm is measured as the natural log of the number of wells it previously drilled. The experience of the operator, rig, and the shared experience of the operator-rig pair are regressors. Note that the experience of the directional drilling company is not an explanatory variable. The directional drilling company's scope of work is limited to operating specialized tools that drill the lateral section of the well, and it is not expected to influence the number environmental incidents that occur. Table 10 of Appendix B considers specifications with alternative experience variables, and the overall results are unchanged.

Through experience, companies may gain knowledge on when accidents are most likely to occur while drilling and be more adept at preventing them. Operator and rigs may develop a better understanding of when it is and is not necessary to perform a test of safety equipment (e.g. valves and pumps that can leak). Interfirm learning may occur primarily through improved communication on safety issues that develops between operators and rigs as their experience working together increases. As noted in Section 1, miscommunication among firms has been cited as a cause of environmental disasters. The Bureau of Environmental Safety and Enforcement (BSEE), which regulates and enforces environmental safety in U.S. offshore oil operations, states that among operators and contractors, "inadequate, incomplete communications remains one of the most common causes of major accidents.." (BSEE, 2013).

Operator and rig fixed effects are included to account for time-invariant unobservables that may cause environmental incidents (e.g. management quality or safety culture). The time fixed effect term (λ_t) encompasses month-of-year and year-quarter fixed effects.

The number of days spent drilling a well ($Days_{ort}$) is included as a control variable. As a well takes longer to drill, the opportunities for incidents (e.g. spills, fires, blowouts) increases. However, days spent drilling a well ($Days_{ort}$) is potentially endogenous. This may be the case if there is feedback between the time required to drill a well and the number of environmental incidents that occur. Environmental incidents may prolong the time it takes to drill a well by temporarily stopping operations. While the coefficient estimate for the regressor $Days_{ort}$ is not of primary interest in this analysis, its endogeneity may bias the coefficient estimates for the experience variables. This occurs if there is a correlation between the days spent drilling and experience, which is expected if firms are becoming more productive (i.e. drilling faster) with greater experience.

To correct for this possible endogeneity, a valid instrumental variable (IV) is required: it must be correlated with the amount of time spent drilling and uncorrelated with unobservables that influence environmental incidents. The depth of a well is a potential instrument. It is correlated with the drilling time since deeper and longer wells take more time to complete, and it is unlikely that well depth is correlated with factors that cause incidents (e.g. a tank leaking at the surface). Results presented in Section 6.2 show depth is well correlated with drilling time and is not a weak instrument. The model is exactly identified because there is only one instrumental variable, so it not possible to test for overidentification. However, it appears unlikely that a well's depth would be correlated with the occurrence of environmental incidents (e.g. a spill occurring at the surface).

A second identification issue is that safety effort is not observed. Company level expenditures on environment, health, and safety are not publicly available, and information would not likely be broken down by well. This section provided a conceptual framework where experience did not influence a firm's optimal choice of safety effort. Under this assumption, while safety effort is omitted from equation 5, it is not correlated with experience and thus does not bias the coefficient estimates. If this assumption is relaxed, so that experience affects a firm's optimal choice of safety effort, the coefficient estimate for the experience variables will be biased. As long as greater experience improves the marginal effect that safety effort has on incidents (i.e. more experience causes the incremental safety effort to go farther in reducing incidents), this will lead to a positive correlation between experience and safety effort. Failing to include safety effort in the estimation models will thus bias the coefficient estimates for experience downward (toward evidence of learning).

Table 5: Summary Statistics for Environmental Incidents

Variable	Obs	Mean	Std. Dev.	Min	Max	P50
Incidents per Well						
Environmental Incidents	4967	.039	.215	0	3	0
Non-Contained Incidents	4967	.004	.069	0	2	0
Contained Incidents	4967	.035	.203	0	3	0
Volumes Spilled						
Oil Spilled (US gallons)	192	59.7	393.2	0	4032	0
Brine Spilled (US gallons)	192	210.9	994.1	0	9240	0
Days until Reported	192	2.0	7.3	0	69	1

Incidents per Well is the number of environmental incidents that occur per well drilled. There are 342 additional observations in the empirical analysis for environmental incidents because fewer covariates are required and fewer observations are lost due to missing values. Volumes Spilled is the amount of oil and brine spilled in reported incidents. 192 incidents are reported to have occurred while drilling 172 different wells. Data on oilfield environmental incidents sourced from the North Dakota Department of Health. Non-contained/contained refers to whether an incident was limited to the boundaries of a facility, drill site, etc.

Table 5 presents data on environmental incidents, which are sourced from the North Dakota Department of Health (North Dakota Department of Health, 2015). These incidents include oil or saltwater leaks from tanks and valves, well blowouts, and equipment failures. For 172 wells, at least one incident was reported to have occurred while drilling. This represents about 3.5% of all wells in the sample. A total of 192 incidents occurred, of which 172 were reported to be contained (e.g. oil does not spill outside of the drill site) and 20 were not contained. The volume of oil and brine spilled during an incident are often reported to be zero. For these incidents, no volumes may have been spilled or it is possible that the exact volume was unknown. The average quantity of oil spilled per incident is 60 gallons with a minimum of zero and a maximum of 4,032 gallons.

6.2 Environmental Safety

Table 6 presents the estimation results for equation 5 where the dependent variable is the number of environmental incidents that occur while drilling a well. Columns 1 and 2 show evidence of interfirm learning among operators and rigs. In column 1, the coefficient estimate for the joint experience of the operator and rig is -0.013 (p=0.089). In column 2, when instrumenting for the days spent drilling a well ($Days$) with the well's depth, the coefficient estimate slightly smaller in magnitude but still statistically significant (p=0.098). The first-stage results show no evidence of a weak instrument (F-stat=353.71). Operator-rig fixed effects are included in column 3 (without the IV) and in column 4 (with the IV), and the coefficient estimates for the joint experience of the operator and rig become statistically indistinguishable from zero.

These results highlight that operator-rig pair unobservables may be an important determinant of environmental incidents. Including operator-rig fixed effects causes the coefficient estimates for the shared experience variable (LnE_{ort}) to become smaller in magnitude and lose statistical significance. This is consistent with the presence of unobservables specific to an operator-rig pair that are 1) positively correlated with the joint experience of an operator-rig pair and 2) negatively correlated with the occurrence of environmental incidents. Firms with similar safety protocols or preferences for risk may be more adept at preventing incidents when drilling with each other and as a result more likely to work together. Thus, not only do firm-level attributes affect environmental safety, but it appears the characteristics of the pair of firms engaged in drilling matters.

Table 7 shows results for equation 5 for only non-contained environmental incidents. These are incidents that were not contained within the boundary of the well site. The results generally mirror the previous table. When operator-rig fixed effects are excluded, there is evidence of interfirm learning in environmental performance. However, when including operator-rig fixed effects, the coefficients estimates become statistically indistinguishable from zero at any reasonable level.

Table 6: Regression Results- Environmental Incidents

	(1) Env Non-IV	(2) Env IV	(3) Env Non-IV	(4) Env IV
LnE_{ot}	0.003	0.003	0.016	0.014
	(0.010)	(0.009)	(0.012)	(0.011)
LnE_{rt}	0.003	0.005	-0.003	-0.002
	(0.011)	(0.009)	(0.013)	(0.012)
LnE_{ort}	-0.013*	-0.012*	-0.012	-0.008
	(0.008)	(0.007)	(0.014)	(0.013)
Days	0.001**	0.003**	0.001*	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	353.71	N/A	331.43
N	4967	4967	4967	4967

The dependent variable is the number of environmental incidents reported to occur while drilling a well. Standard errors clustered on rig are shown in parentheses. Clustering on rig generally yields similar but slightly larger standard error estimates compared to clustering on operator or year-qtr. First stage F-statistics are from the first stage regression results of the IV, where the well's total depth instruments for *Days*.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Regression Results- Non-Contained Environmental Incidents

	(1)	(2)	(3)	(4)
	Env	Env	Env	Env
	Non-IV	IV	Non-IV	IV
LnE_{ot}	0.003	0.003	0.004	0.004
	(0.003)	(0.003)	(0.005)	(0.005)
LnE_{rt}	0.003	0.004	0.005	0.006
	(0.003)	(0.003)	(0.005)	(0.004)
LnE_{ort}	-0.004*	-0.004	-0.007	-0.006
	(0.002)	(0.003)	(0.005)	(0.005)
Days	0.000	0.000	0.000	0.001**
	(0.000)	(0.000)	(0.000)	(0.000)
Firm FE	Yes	Yes	Yes	Yes
Year-Qtr FE	Yes	Yes	Yes	Yes
Month-of-Year FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	353.71	N/A	331.43
N	4967	4967	4967	4967

The dependent variable is the number of non-contained environmental incidents reported to occur while drilling a well. Standard errors clustered on rig are shown in parentheses. Clustering on rig generally yields similar but slightly larger standard error estimates compared to clustering on operator or year-qtr. First stage F-statistics are from the first stage regression results of the IV, where the well's total depth instruments for *Days*.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8 present the results when considering only incidents that were contained within the well site. There is no evidence of relationship-specific learning, nor of learning by individual firms, in reducing the occurrence of contained incidents. The coefficient estimate for joint operator-rig experience is negative but statistically indistinguishable from zero across the four specifications.

The difference in results for contained and non-contained incidents may be explained by non-contained incidents being more costly to firms. In non-contained incidents, oil or brine may spill onto areas near a drilling site and require the firm to compensate affected landowners. Non-contained incidents may trigger a follow-up by the State of North Dakota (North Dakota Department of Health, 2015), and these incidents may be more costly to clean up. Thus firms may have a greater incentive to prevent non-contained incidents relative to contained ones.

7 Conclusion

This paper has investigated the role of interfirm learning economies in increasing drilling productivity and environmental safety. The analysis demonstrates some evidence that relationship-specific learning occurs between operators and rigs engaged in drilling oil wells in the Bakken Shale Play. Yet the evidence is not robust across all empirical specifications. This contrasts with the strong evidence for relationship-specific learning in drilling of vertical wells in Texas (Kellogg, 2011). A possible explanation for these differential results is that as the number of firms engaged in a production process grows, cultivation of interfirm relationships that lead to learning becomes more difficult. Future work may explore how the nature of firm-to-firm relationships and production processes influence interfirm learning.

Despite the somewhat mixed evidence for relationship-specific learning, companies appear to account for it by maintaining relationships. This strengthens the evidence for relationship-specific learning and demonstrates that firm behavior is consistent with awareness of this

Table 8: Regression Results- Contained Environmental Incidents

	(1) Env Non-IV	(2) Env IV	(3) Env Non-IV	(4) Env IV
LnE_{ot}	-0.000	0.000	0.012	0.011
	(0.010)	(0.009)	(0.011)	(0.010)
LnE_{rt}	-0.001	0.001	-0.009	-0.008
	(0.010)	(0.009)	(0.012)	(0.011)
LnE_{ort}	-0.009	-0.008	-0.005	-0.002
	(0.007)	(0.007)	(0.013)	(0.011)
Days	0.001^{**}	0.002^{**}	0.001	0.002^{*}
	(0.000)	(0.001)	(0.001)	(0.001)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	353.71	N/A	331.43
N	4967	4967	4967	4967

The dependent variable is the number of contained environmental incidents reported to occur while drilling a well. Standard errors clustered on rig are shown in parentheses. Clustering on rig generally yields similar but slightly larger standard error estimates compared to clustering on operator or year-qtr. First stage F-statistics are from the first stage regression results of the IV, where the well's total depth instruments for *Days*.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

learning and its associated benefits to productivity. This would imply that attempts by large conventional oil producing countries to lower oil prices in hopes of reduce the competitiveness of US oil shale producers may be successful, at least temporarily. However, the fact that the magnitude of this interfirm is small would imply that US oil shale competitiveness will not be altered significantly.

There is little evidence of within-firm or interfirm learning in improving environmental safety. However, this paper shows that the characteristics of a pair of two firms working together appear to influence environmental safety. This is particularly relevant for understanding the underlying causes of environmental disasters. There is opportunity for further work on refining the empirical estimation of firm learning in environmental safety by including controls for firm-level safety effort as well as identifying other contributors to environmental incidents.

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Appendix A

This appendix provides additional analysis on interfirm learning economies. First, it attempts to provide a better understanding of what drives interfirm learning. Second, it examines whether relationship-specific learning occurs at the level of the operator and drilling contractor, which owns the rig. No two wells are identical, but wells drilled in the same field by the same operator may have similar characteristics (e.g. depth and design of curve and lateral section). The relationship-specific learning observed between operators and rigs may result from rigs becoming more proficient at drilling particular types of wells drilled for an operator. This is analogous to employees of a firm becoming more efficient as they learn the practices and processes specific to their employer. Similarly, in the case of rig-directional driller learning, the contractors may learn together as they drill a particular type of well for an operator, but this learning may not transfer when drilling potentially different kinds of wells for other operators.

Drilling contractors typically own many rigs. Relationship-specific learning may occur at the level of the rig or the drilling contractor. Learning that occurs at the operator-rig level may result as a rig's crew and operator's representative work together. This learning may transfer to other rigs employed by the same operator. Drilling contractors with multiple rigs may actively work to diffuse knowledge among rigs working for the same operator, or crew members may be transferred to other rigs drilling wells for the same operator. Similar mechanisms may be at work for learning specific to rigs and directional drillers.

Table 9 presents several results relating to operator-rig learning. Columns 1 and 2 show the estimation results when operator-rig experience is included with and without operator-rig fixed effects. In column 1, without operator-rig effects, the coefficient estimate for logged operator-rig experience is 0.020 ($p=0.110$). When operator-rig fixed effects are included in column 2, the coefficient becomes 0.070 ($p<0.001$). The variable for logged operator-rig experience within a field (LnE_{orft}) is included in column 3 (without operator-rig effects) and column 4 (with operator-rig fixed effects), and the coefficient estimates are -0.091

(p=0.003) and -0.096 (p=0.006), respectively. These coefficient estimates are likely a result of the high collinearity (0.98 correlation coefficient) between the experience of an operator-rig pair within a field (LnE_{orft}) and the experience of a rig in a field (LnE_{rft}). Wells drilled by a rig within a field are almost always drilled for the same operator; note that the coefficient estimate for rig experience within a field increases and becomes highly significant once the variable LnE_{orft} is included. These results suggest that it is not possible to distinguish the importance of rig experience within a field and operator-rig experience within a field. In columns 5 and 6, variables are included for the logged experience of the drilling contractor (LnE_{ct}) and joint experience of the drilling contractor and operator (LnE_{oct}). The coefficient estimate for the operator-drilling contractor joint experience variable is insignificant at any reasonable level in column 5 (without operator-rig fixed effects) and in column 6 (with operator-rig fixed effects).

Table 9: Regression Results

	(1)	(2)	(3)	(4)	(5)	(6)
	lnRate	lnRate	lnRate	lnRate	lnRate	lnRate
Operator	0.001	-0.029	0.002	-0.030	-0.006	-0.046*
LnE_{ot}	(0.017)	(0.022)	(0.017)	(0.023)	(0.017)	(0.025)
Operator-Field	0.013	0.003	0.018*	0.007	0.013	0.003
LnE_{oft}	(0.009)	(0.010)	(0.010)	(0.010)	(0.009)	(0.010)
Field	0.011	0.010	0.010	0.009	0.013	0.011
LnE_{ft}	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)
Rig	0.071***	0.044**	0.065***	0.040*	0.090***	0.060***
LnE_{rt}	(0.017)	(0.021)	(0.016)	(0.021)	(0.018)	(0.022)
Directional	-0.039**	-0.053***	-0.039**	-0.053***	-0.040**	-0.053**
LnE_{dt}	(0.017)	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)
Rig-Field	0.015	0.008	0.099***	0.100***	0.014	0.008
LnE_{rft}	(0.011)	(0.011)	(0.030)	(0.035)	(0.011)	(0.011)
Directional-Field	-0.005	0.004	-0.005	0.004	-0.004	0.005
LnE_{dft}	(0.008)	(0.009)	(0.008)	(0.009)	(0.008)	(0.009)
Operator-Rig	0.020	0.070***	0.028**	0.076***	0.012	0.058*
LnE_{ort}	(0.012)	(0.021)	(0.012)	(0.020)	(0.014)	(0.023)
Op-Rig-Field			-0.091***	-0.096***		
LnE_{orft}			(0.031)	(0.035)		
Drill Contractor					-0.058***	-0.063***
LnE_{ct}					(0.018)	(0.024)
Op-Drilling Contractor					0.010	0.027
LnE_{oct}					(0.011)	(0.018)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Operator-Rig FE	No	Yes	No	Yes	No	Yes
Year-Qtr FE	Yes	Yes	Yes	Yes	Yes	Yes
Field FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	4625	4625	4625	4625	4625	4625

The dependent variable is the log rate of drilling. Standard errors clustered on field in parentheses. LnE_{ct} and LnE_{oct} are logged drilling contractor and operator-drilling contractor experience, respectively. Firm fixed effects include operator, rig, and directional drilling level effects.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix B

Table 10 presents alternative specifications for the learning in environmental safety model in equation 5. Columns 1 and 2 include the experience of only the operator and only the rig, respectively. Column 3 includes the experience of the operator, rig, and the operator-rig pair, and column 4 adds the experience of the directional drilling company. Tables 11–13 show estimation results for equation 5 where the dependent variable is changed to the spilled volumes of oil, brine, and oil and brine combined, respectively. While there is some evidence of reduction in spilled volumes of brine (Table 12) and total oil and brine (Table 13), the accuracy of data on reported spill volumes is unknown. In the 192 incidents reported, 146 incidents reported zero volumes of oil and brine had spilled. It is unclear if no volumes of oil and brine were spilled, the amount spilled was unknown, or left unreported.

Table 14 displays the types of environmental incidents reported during drilling operations. The data source is North Dakota Department of Health (2015).

Table 10: Regression Results- Environmental Incidents Alternative Specifications

	(1) Non-IV Env	(2) Non-IV Env	(3) Non-IV Env	(4) Non-IV Env
LnE_{ot}	-0.009		0.003	-0.002
	(0.013)		(0.010)	(0.011)
LnE_{rt}		-0.004	0.003	-0.000
		(0.008)	(0.011)	(0.012)
LnE_{ort}			-0.013*	-0.015*
			(0.008)	(0.009)
LnE_{dt}				0.017
				(0.011)
$Days$	0.002***	0.001**	0.001**	0.001**
	(0.001)	(0.000)	(0.001)	(0.001)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	No	No
N	4967	4967	4967	4641

The dependent variable is the number of environmental incidents reported to occur while drilling a well. Standard errors clustered on rig are shown in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 11: Regression Results- Oil Volumes Spilled

	(1) Non-IV Oil	(2) IV Oil	(3) Non-IV Oil	(4) IV Oil
LnE_{ot}	-114.165*	-109.684*	-99.209	-108.173
	(66.435)	(62.848)	(73.597)	(69.723)
LnE_{rt}	-18.107	0.192	-136.536	-132.431
	(42.563)	(39.726)	(88.950)	(84.748)
LnE_{ort}	17.484	31.737	134.972	158.869*
	(25.649)	(24.046)	(96.262)	(94.026)
$Days$	2.252	17.250**	1.946	12.219*
	(1.575)	(7.187)	(1.719)	(6.587)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	343.05	N/A	320.69
N	4892	4857	4892	4857

The dependent variable is the gallons of oil reportedly spilled while drilling. Standard errors clustered on rig are shown in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 12: Regression Results- Brine Volumes Spilled

	(1) Non-IV Brine	(2) IV Brine	(3) Non-IV Brine	(4) IV Brine
LnE_{ot}	-601.777	-591.733	-267.964***	-282.754***
	(476.022)	(428.812)	(102.342)	(95.584)
LnE_{rt}	173.997	233.117	-59.462	-51.747
	(179.640)	(186.108)	(129.092)	(104.962)
LnE_{ort}	-75.788	-46.752	57.997	86.902
	(92.158)	(80.014)	(127.967)	(108.147)
$Days$	-0.760	39.009^{+}	-0.431	12.921
	(3.005)	(22.802)	(3.102)	(11.005)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	316.64	N/A	304.32
N	4767	4733	4767	4733

The dependent variable is the gallons of brine reportedly spilled while drilling. Standard errors clustered on rig are shown in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 13: Regression Results- Oil and Brine Volumes Spilled

	(1) Non-IV Spill	(2) IV Spill	(3) Non-IV Spill	(4) IV Spill
LnE_{ot}	-751.129	-732.013	-394.600**	-422.160***
	(556.754)	(500.754)	(152.451)	(142.648)
LnE_{rt}	171.890	252.128	-207.168	-196.739
	(207.888)	(211.373)	(188.568)	(167.258)
LnE_{ort}	-74.899	-29.832	202.027	261.307
	(98.803)	(89.245)	(200.666)	(185.961)
$Days$	2.257	59.430**	3.245	28.940**
	(3.775)	(26.606)	(3.871)	(13.975)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Operator-Rig FE	No	No	Yes	Yes
1st Stage F-stat	N/A	309.07	N/A	295.70
N	4720	4686	4720	4686

The dependent variable is the gallons of oil and brine reportedly spilled while drilling. Standard errors clustered on rig are shown in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 14: Types of Environmental Incidents

Incident Type	Count	Percent
Blowout	3	1.56
Fire	7	3.65
Pipeline Leak	10	5.21
Pump Leak	12	6.25
Tank Leak	8	4.17
Tank Overflow	46	23.96
Truck Overflow	2	1.04
Valve/Piping Connection Leak	56	29.17
Other	48	25
Total	192	100

Source: North Dakota Department of Health (2015). Reported Incidents include both contained and non-contained environmental incidents that occurred during well drilling.

Table 15: Logit and OLS Estimation Results for Relationship Termination (October 2007–September 2009)

	(1) Logit Terminate	(2) Logit Terminate	(3) Logit Terminate	(4) OLS Terminate	(5) OLS Terminate	(6) OLS Terminate
$RelExp_{or}$	-0.53**		-0.86*	-0.06***		-0.11***
	(0.22)		(0.51)	(0.02)		(0.02)
$RelExp_{r}$		-0.01	0.38		-0.00	0.05***
		(0.13)	(0.44)		(0.03)	(0.01)
Constant	0.24	-0.81	-0.06	0.45***	0.31**	0.42***
	(0.57)	(0.57)	(0.57)	(0.11)	(0.12)	(0.11)
N	37	37	37	37	37	37

Robust standard errors in parentheses. The *Terminate* indicates if an operator-rig relationships ends; the variable is equal to 0/1 for 26/11 of 37 observations. *Terminate* = 1 if a operator-rig drilled a well between October 2007 and September 2008 and did not drill at least one well between October 2008 and September 2009.

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

Appendix C

Tables 15-16 present estimation results for equation 4 when the sample period is varied. In Table 15, the sample is limited to operators and rigs that drilled wells during October 2007–September 2008. The dependent variable ($Terminate_{or}$) in equation 4 is equal to 1 if the operator-rig pair did not drill another well over the next 12 months (October 2008–September 2009) and equal to 0 if the pair drilled at least one well together.

Table 16 modifies the sample period to September 2006–August 2010. An operator-rig pair relationship that existed during September 2006–August 2008 is considered to terminate if the pair did not drill a well in the subsequent 24 months (September 2008–August 2010). Lastly, when the sample period is changed to November 2006–October 2010, the coefficient estimates for the relative experience variable ($RelExp_{or}$) become insignificant. Although this is largely driven by one relationship with relatively high experience that terminates. When omitting this observation, the coefficient estimate for the relative experience variable is significant at the 5% level (column 1 specification) and 1% level (column 4 specification).

Table 16: Logit and OLS Estimation Results for Relationship Termination (September 2006–August 2010)

	(1) Logit Terminate	(2) Logit Terminate	(3) Logit Terminate	(4) OLS Terminate	(5) OLS Terminate	(6) OLS Terminate
$RelExp_{or}$	-2.11*		-2.18**	-0.05***		-0.09***
	(1.10)		(1.08)	(0.01)		(0.01)
$RelExp_{r}$		-0.15	0.22		-0.02	0.04***
		(0.16)	(0.15)		(0.02)	(0.01)
Constant	2.65*	-0.19	2.34*	0.48***	0.43***	0.45***
	(1.41)	(0.56)	(1.41)	(0.11)	(0.11)	(0.11)
N	37	37	37	37	37	37

Robust standard errors in parentheses. The *Terminate* indicates if an operator-rig relationships ends; the variable is equal to 0/1 for 25/12 of 37 observations. $Terminate = 1$ if a operator-rig drilled a well between September 2006 and August 2008 and did not drill at least one well between September 2008 and August 2010.

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