The Price Responsiveness of Shale Producers: Evidence From Micro Data

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Background: The conventional story

- Theoretical models and empirical analysis of U.S. conventional oil extraction find no response in production to oil price changes
  - Conventional oil wells are constrained by reservoir pressure and gradually decline (see e.g. Pesaran (1990), Ramcharran (2002) and Anderson, Kellogg and Salant (2018)).

- Exploration and drilling is risky and expensive. And once oil is discovered, development is subject to long lead times.
- It is costly to regulate the flow of crude oil once a well is producing.

$\Rightarrow$ Conventional wisdom: vertical short-run oil supply curve.

Background: The U.S. Shale Oil Boom

Fracking has brought a new dynamic to global oil markets
Economist, June 2016

- During the last 15 years, the U.S. has experienced an massive increase in crude oil production due to the surge in shale oil. data
- This massive production surge is made possible by the development of hydraulic fracturing (so-called "fracking") and horizontal drilling technologies.
- A key feature of fracking is that it allows for a more flexible production process compared to conventional oil, as wells can be re-fractured over time.
- Implies that oil companies can be forward looking, reducing the extraction rate when market conditions are poor, or resuming extraction when conditions improve, see Bornstein, Krusell, and Rebelo (2021).
- Plausibly, this has increased the prices responsiveness of oil producers

Shale well flexibility

Claim: Shale oil wells are more *flexible* than conventional oil wells

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- Development of new wells (extensive margin)
  - Shale wells have front-loaded production profiles: large incentives to better time the revenue stream.

Front-loaded production profile

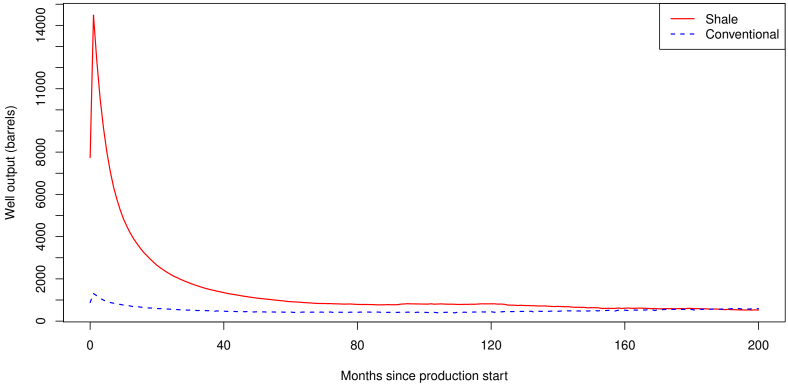

Figure: Mean production profiles by technology for 10 U.S. states
Source: Rystad Energy (own calculations)

Shale well flexibility

Claim: Shale oil wells are more *flexible* than conventional oil wells

- Development of new wells (extensive margin)
  - Shale wells have front-loaded production profiles: large incentives to better time the revenue stream.
  - If well completion is postponed, shale wells can be producing in matter of days (5 on average).
  - Shale wells can be drilled and completed in pads — multiple wells concentrated in a small geographic location.

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- Development of new wells (extensive margin)
  - Shale wells have front-loaded production profiles: large incentives to better time the revenue stream.
  - If well completion is postponed, shale wells can be producing in matter of days (5 on average).
  - Shale wells can be drilled and completed in pads — multiple wells concentrated in a small geographic location.
- Increase production from existing wells (intensive margin)
  - Existing shale wells can be restimulated ("refractured")

Shale wells can be restimulated

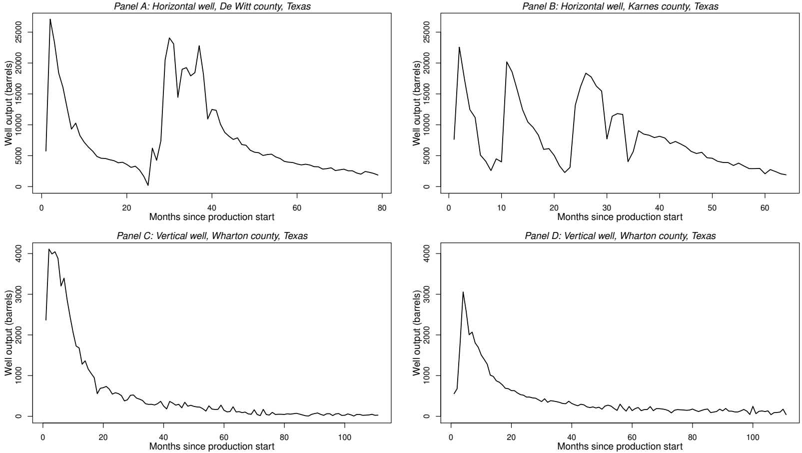

Figure: Example well production profiles—shale and conventional
Source: Rystad Energy

What we do

- Estimate price responsiveness of U.S. oil producers using a novel proprietary dataset compiled by Rystad Energy.
  - Covering production from all reported shale oil wells (200,000 unique wells) in the 10 largest U.S. oil producing states for the period 2005:M01–2017:M12
- Findings
  1. Document that shale oil producers respond differently to price signals than conventional oil producers.
  2. Document large heterogeneity in the estimated responses across the various shale wells, suggesting that aggregation bias is an important issue for this kind of analysis
  3. Exploring potential heterogeneities, we find responses to be stronger for the largest oil producing firms, among wells that are spaced further apart and in regions where the density of shale wells is higher.

Relation to literature

- Newell and Prest (2019) and Bjørnland et al. (2021) have analyzed the price-responsiveness of U.S. shale oil producers using high frequent micro data reaching opposite conclusions
  - Differ in data set and employ notably different modelling frameworks

- We contribute to these studies by:
  1. Showing that the key difference that accounts for the opposite findings is the inclusion of the futures-spot spread to capture expectations about future prices
  2. Using a data set that covers production from all reported shale oil wells in the 10 largest U.S. oil producing states for the period 2005:M01–2017:M12
  3. Exploring potential heterogeneities along a number of dimensions and document that micro data is key to obtaining reliable estimates of the aggregate price response of oil producers.

The data

- A comprehensive dataset provided by Rystad Energy, covering all shale wells across 10 U.S. states as well as conventional wells in Texas.
    - 200,000 shale wells and 150,000 conventionally drilled wells.
    - Monthly frequency, 2005:M01–2017:M12.
- We have access to production data as well as other well characteristics such as ownership, distance to closest neighbouring well, drilling depth, location etc.
- Data is collected from official sources such as local government agencies, market intelligence and oil company reports.
- Data is adjusted for differences in reporting standards and classifications across states/provinces

Map of wells in sample

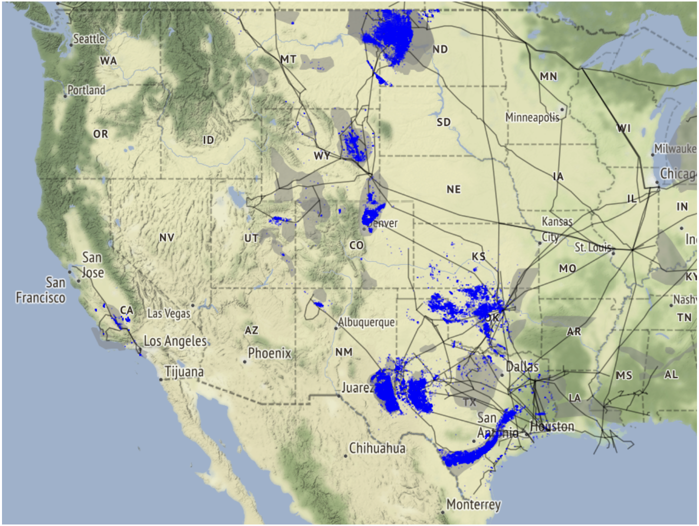

Figure: Location of shale wells in sample. North Dakota, Oklahoma and Texas are the major shale states.

Source: Rystad Energy

Model

Do oil producers respond to changes in the oil price?

- No consensus in the literature on the appropriate modelling strategy
- We combine features of Newell and Prest (2019) and Bjørnland et al. (2021)
- From Newell and Prest (2019): estimation in log-levels, well-age FE with cubic spline and Henry Hub natural gas price.
- From Bjørnland et al. (2021): year and well FE, both the WTI spot price and the spot-futures spread, and macro control variables.
- Importantly, the spread between the WTI spot price and the NYMEX WTI futures price $[\ln P_t - \ln F_{t,t+3}]$ is capturing forward-looking behaviour.

→ Estimate fixed-effects model for shale wells in California, Colorado, Kansas, Montana, New Mexico, North Dakota, Oklahoma, Texas, Utah and Wyoming.

Model

Do oil producers respond to changes in the oil price?

$$\ln q_{it} = \eta_{oil} \ln P_t^{oil} + \eta_F [\ln P_t^{oil} - \ln F_{t,t+3}] + \eta_{gas} \ln P_t^{gas} + X_t + g(Age_{it}) + \lambda_y + \mu_i + \varepsilon_{it}$$

where $\ln q_{it}$ is log-production for well i, $\ln P_t^{oil}$ the log of the WTI crude oil price, $\ln F_{t,t+3}$ the log of NYMEX 3-month futures price of oil, $\ln P_t^{gas}$ the log of the Henry Hub natural gas price, X_t is a vector of macro controls, $g(Age_{it})$ is a cubic spline well-age FE, μ_i is well FE and λ_y is year FE. Knots for the cubic spline is set at every 12th month. Standard errors are clustered on well-time.

Aggregated data vs. panel data

Shale vs. conventional wells on aggregated and panel data

Specification	(1)	(2)	(3)	(4)
	$\ln q_t$			
	Shale		Conventional	
η_{oil}	0.02	-0.06^{*}	-0.02	-0.01
	(0.07)	(0.04)	(0.04)	(0.03)
η_F	-0.66	0.68^{***}	-0.34	-0.16
	(0.47)	(0.25)	(0.25)	(0.24)
η_{gas}	-0.03	-0.03	0.00	-0.01
	(0.04)	(0.03)	(0.02)	(0.02)
$\eta_{oil} + \eta_F$	-0.64	0.62^{***}	-0.35	-0.17
	(0.45)	(0.23)	(0.23)	(0.22)
Macro controls	Yes	Yes	Yes	Yes
Well FE	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes
Linear trend	Yes	No	Yes	No
Well Age FE	No	Spline[3]	No	Spline[3]
First observation	2005:M01	2005:M02	2005:M01	2005:M02
Last observation	2017:M12	2017:M12	2017:M12	2017:M12
N		58,422		84,760
$N \times T$	156	2,649,951	156	5,700,878
$\bar{R}^2$	0.72	0.77	0.85	0.82
Clustering	Time	Well-Time	Time	Well-Time
Num. clusters	156	155	156	154

Table: Columns 1 and 2 are for shale wells while columns 3 and 4 are on vertically drilled Texas wells. Columns 1 and 3 are on aggregated data and columns 2 and 4 are on our well-level panel.

Unconditional quantile regression analysis

Unconditional quantile regression on log-level full cross-section

Distributional stat.	Q1	Q5	Q25	Q50	Q75	Q95	Q99
η_{oil}	0.17	0.09**	−0.01	−0.02	−0.10**	−0.21**	−0.25*
	(0.10)	(0.04)	(0.04)	(0.04)	(0.04)	(0.10)	(0.15)
η_F	0.98	0.12	0.36	0.10	0.48*	1.96***	2.30***
	(0.60)	(0.18)	(0.24)	(0.27)	(0.28)	(0.47)	(0.63)
η_{gas}	−0.01	−0.03*	−0.01	−0.02	−0.03	−0.05	0.00
	(0.05)	(0.02)	(0.02)	(0.03)	(0.03)	(0.04)	(0.05)
$\eta_{oil} + \eta_F$	1.15	0.21	0.35	0.09	0.38	1.75***	2.05***
	(0.71)	(0.15)	(0.22)	(0.25)	(0.26)	(0.40)	(0.52)
Macro controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Well FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Well Age FE	Spline^3	Spline^3	Spline^3	Spline^3	Spline^3	Spline^3	Spline^3
Dip dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First observation	2005:M02	2005:M02	2005:M02	2005:M02	2005:M02	2005:M02	2005:M02
Last observation	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12
N	58,422	58,422	58,422	58,422	58,422	58,422	58,422
$N \times T$	2,649,951	2,649,951	2,649,951	2,649,951	2,649,951	2,649,951	2,649,951
$\bar{R}^2$	0.62	0.59	0.59	0.62	0.57	0.38	0.26
Mean LHS	3.10	4.94	6.37	7.26	8.07	9.26	9.96
Clustering	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time
Num. clusters	155	155	155	155	155	155	155

Table: Unconditional quantile regression estimation results on data in log-levels. *Mean LHS* gives an indication on where in the distribution each percentile is located. A dummy variable is included to control for outliers in the lower tail of the distribution.

Regression results conditional on refracturing and production start

Regression results conditional on refracturing and production start

Specification	(1)	(2)	(3)	(4)
	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$
η_{oil}	-0.06^{*}	-0.06^{*}	-0.06^{*}	-0.06^{*}
	(0.04)	(0.04)	(0.04)	(0.04)
$\eta_{oil} \times (start_{it} = 1)$		0.07^{***}		0.07^{***}
		(0.01)		(0.01)
$\eta_{oil} \times (refractured_{it} = 1)$			-0.19^{***}	-0.20^{***}
			(0.01)	(0.01)
η_F	0.68^{***}	0.66^{***}	0.67^{***}	0.65^{***}
	(0.25)	(0.24)	(0.24)	(0.24)
$\eta_F \times (start_{it} = 1)$		0.26		0.25
		(0.39)		(0.39)
$\eta_F \times (refractured_{it} = 1)$			1.90^{**}	1.93^{**}
			(0.76)	(0.75)
η_{gas}	-0.03	-0.03	-0.03	-0.03
	(0.03)	(0.03)	(0.03)	(0.03)
Macro controls	Yes	Yes	Yes	Yes
Well FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Well Age FE	Spline^3	Spline^3	Spline^3	Spline^3
First observation	2005:M02	2005:M02	2005:M02	2005:M02
Last observation	2017:M12	2017:M12	2017:M12	2017:M12
N	58,422	58,422	58,422	58,422
$N \times T$	2,649,951	2,649,951	2,649,951	2,649,951
$\bar{R}^2$	0.77	0.77	0.77	0.77
Clustering	Well-Time	Well-Time	Well-Time	Well-Time
Num. clusters	155	155	155	155

Table: $refractured_{it}$ is a dummy variable equal to 1 if the well is likely to have been refractured at time t. $start_{it}$ is a dummy variable equal to 1 if t is the first full production month for well i.

Lessons so far

- No evidence of price-responsiveness for conventional wells.
- The use of micro data is key to obtaining reliable estimates of the aggregate price response of oil producers (aggregation bias)
- Strong response for shale wells
  - This conclusion does not change if we estimate our model in log-difference form
- The responsiveness of shale wells is associated with the two margins of which shale producers can use to time their production decisions: well completion and well refracturing.

Additional sources of heterogeneity

Panel A: Firm size and price response		Panel B: Well spacing and price response		Panel C: Price response in firm-level panel	
	$\ln(q_{it})$		$\ln(q_{it})$		$\ln(\tilde{q}_{kt})$
η_{oil}	-0.03	η_{oil}	0.11^{**}	η_{oil}	-0.20^{***}
	(0.04)		(0.04)		(0.06)
$\eta_{oil} \times (large_i = 1)$	-0.11^{***}	$\eta_{oil} \times (space_i = 1)$	-0.25^{***}		
	(0.02)		(0.03)		
η_F	0.52^{**}	η_F	-1.04^{***}	η_F	0.80^{**}
	(0.25)		(0.39)		(0.34)
$\eta_F \times (large_i = 1)$	0.57^{**}	$\eta_F \times (space_i = 1)$	2.44^{***}		
	(0.23)		(0.39)		
η_{gas}	-0.03	η_{gas}	-0.03	η_{gas}	-0.01
	(0.03)		(0.03)		(0.04)
$(\eta_{oil} + \eta_F)$	0.49^{**}	$(\eta_{oil} + \eta_F)$	-0.93^{**}	$(\eta_{oil} + \eta_F)$	0.60^{**}
	(0.23)		(0.37)		(0.25)
$(\eta_{oil} + \eta_F) + (\eta'_{oil} + \eta'_F) \times (large_i = 1)$	0.95^{***}	$(\eta_{oil} + \eta_F) + (\eta'_{oil} + \eta'_F) \times (space_i = 1)$	1.26^{***}		
	(0.28)		(0.25)		
Macro controls	Yes	Macro controls	Yes	Macro controls	Yes
Well FE	Yes	Well FE	Yes	Firm FE	Yes
Year FE	Yes	Year FE	Yes	Year FE	Yes
State FE	Yes	State FE	Yes	State FE	Yes
Well Age FE	Spline[3]	Well Age FE	Spline[3]	State-Firm trend	Linear
First observation	2005:M01	First observation	2005:M01	First observation	2005:M01
Last observation	2017:M12	Last observation	2017:M12	Last observation	2017:M12
N	58,422	N	57,273	N	1,050
$N \times T$	2,649,951	$N \times T$	2,597,681	$N \times T$	98,910
$\bar{R}^2$	0.77	$\bar{R}^2$	0.77	$\bar{R}^2$	0.69
Clustering	Well-Time	Clustering	Well-Time	Clustering	Firm-Time
Num. clusters	155	Num. clusters	155	Num. clusters	156

Conclusion

- It has been a widely held belief that oil producers do not respond to oil price changes. We find evidence that the introduction of shale extraction technology has changed this:
- The option to fracture (and refracture) combined with heavily front-loaded production schedules gives strong incentives to better time when to produce.
- We reaffirm previous results in the literature: shale wells responds strongly and positively to favourable oil price signals and conventional wells do not
- We uncover a correspondence between the two decision margins of shale producers—completion and refracturing—and price responsiveness
- Wells operated by the largest firms and wells spaced further apart respond more strongly.
- The price-responsiveness generalizes across state borders and are found to be even stronger within shale plays.

Extra

EXTRA

Introduction: The U.S. Shale Oil Boom is a game changer

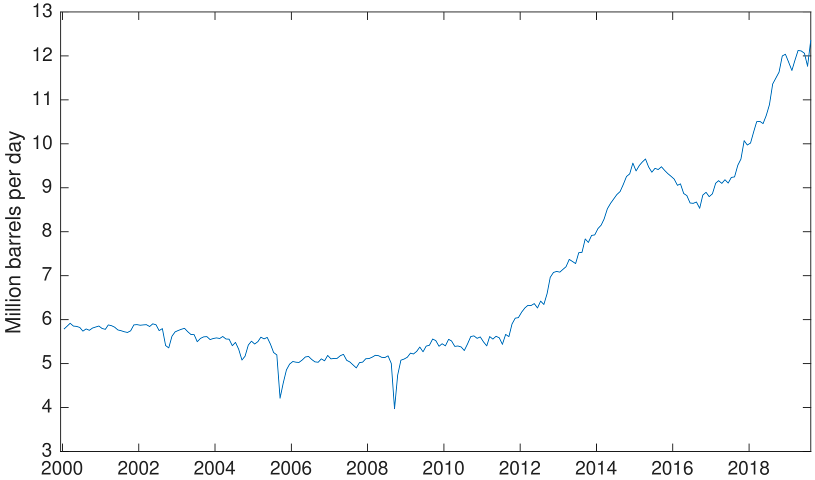

Figure: U.S. crude oil production, 2000–2019.
Source: U.S. Energy Information Administration

back

Summary of state characteristics across a variety of dimensions

Summary of state characteristics

	CA	CO	KS	MT	NM	ND	OK	TX	UT	WY
Share shale 2014	4.19%	84.04%	10.16%	71.62%	59.68%	97.40%	n.a	62.96%	16.05%	44.67%
Share shale 2017	3.68%	93.00%	4.63%	63.31%	78.49%	98.12%	n.a.	75.87%	32.62%	53.64%
HH index full sample	0.31	0.34	0.04	0.14	0.13	0.15	0.14	0.04	0.52	0.22
HH index 2010–	0.31	0.23	0.06	0.13	0.11	0.07	0.06	0.04	0.39	0.16
Market share top 5 firms	87.20%	59.67%	21.04%	71.17%	53.83%	39.45%	21.99%	26.34%	90.27%	45.34%
Market share top 5 firms 2010–	89.52%	83.76%	34.18%	69.41%	61.82%	46.22%	35.12%	36.68%	90.02%	67.22%
Average share of total shale production	0.73%	2.53%	1.59%	12.38%	4.39%	33.10%	4.63%	38.81%	0.24%	1.67%

Table: Summary of state characteristics across a variety of dimensions. *Share shale* refers to the share of oil produced in the state that is from shale wells. *HH index* is the Herfindahl-Hirschmann Index which measures market concentration. The higher number for the HH-index, the closer a market is to a monopoly (i.e, the higher the market's concentration, and the lower its competition). We rank firm size by the number of barrels of crude oil produced. *Total shale production* refers to the total amount of barrels of crude oil produced by shale wells across the ten states. State characteristics data is courtesy of Rystad Energy.

Responsiveness across states

Regression results on log-level state-level data

Subsample	All states	CA	CO	KS	MT	ND	NM	OK	TX	UT	WY
	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$
η_{oil}	-0.06^{*}	-0.04	-0.07	-0.37^{***}	-0.05	-0.11^{***}	0.02	-0.11^{**}	-0.04	-0.06	0.03
	(0.04)	(0.12)	(0.07)	(0.10)	(0.03)	(0.04)	(0.05)	(0.05)	(0.04)	(0.10)	(0.06)
η_{F}	0.68^{***}	0.20	0.95^{**}	1.47^{***}	0.45^{**}	0.89^{***}	0.55	1.04^{***}	0.51^{*}	1.11^{*}	-0.12
	(0.25)	(0.41)	(0.40)	(0.53)	(0.20)	(0.26)	(0.36)	(0.38)	(0.29)	(0.60)	(0.27)
η_{gas}	-0.03	-0.02	-0.01	-0.09	0.00	-0.07^{**}	0.01	0.02	-0.03	0.06	-0.04
	(0.03)	(0.05)	(0.04)	(0.06)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.06)	(0.03)
$\eta_{oil}+\eta_{F}$	0.62^{***}	0.16	0.88^{**}	1.10^{**}	0.40^{**}	0.78^{***}	0.58	0.93^{***}	0.46^{*}	1.05^{**}	-0.09
	(0.23)	(0.37)	(0.34)	(0.46)	(0.19)	(0.23)	(0.36)	(0.35)	(0.27)	(0.53)	(0.24)
Macro controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Well FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Well Age FE	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]	Spline[3]
First observation	2005:M02	2005:M02	2007:M04	2006:M05	2005:M02	2005:M02	2005:M04	2006:M03	2005:M02	2005:M04	2005:M02
Last observation	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12
N	58,422	761	4,286	388	1,255	12,893	3,615	5,526	28,063	219	1,416
$N \times T$	2,649,951	38,759	150,211	13,511	110,560	705,220	161,652	236,259	1,164,466	9,612	59,701
$\bar{R}^2$	0.77	0.60	0.77	0.77	0.75	0.65	0.78	0.84	0.78	0.82	0.81
Clustering	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time
Num. clusters	155	155	129	139	155	155	153	142	155	153	155

Responsiveness across shale plays

Estimation results for shale play level data

Subsample	Anadarko (OK)	Mississippian (OK)	Bakken (ND)	Eagle Ford (TX)	Permian (TX)
	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$	$\ln(q_{it})$
η_{oil}	-0.10^{*}	-0.15^{**}	-0.12^{***}	-0.06	-0.01
	(0.06)	(0.06)	(0.04)	(0.06)	(0.07)
η_F	0.82^{**}	1.59^{***}	0.92^{***}	0.34	1.09^{***}
	(0.40)	(0.40)	(0.27)	(0.41)	(0.41)
η_{gas}	0.03	-0.02	-0.07^{**}	-0.03	-0.06
	(0.04)	(0.04)	(0.03)	(0.04)	(0.04)
$\eta_{oil} + \eta_F$	0.72^{**}	1.44^{***}	0.80^{***}	0.28	1.07^{***}
	(0.36)	(0.37)	(0.24)	(0.36)	(0.37)
Macro controls	Yes	Yes	Yes	Yes	Yes
Well FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Well Age FE	Spline^3	Spline^3	Spline^3	Spline^3	Spline^3
First observation	2006:M09	2008:M12	2005:M02	2006:M11	2005:M02
Last observation	2017:M12	2017:M12	2017:M12	2017:M12	2017:M12
N	1,390	1,658	12,195	14,869	3,089
$N \times T$	74,474	74,489	646,096	655,691	104,092
$\bar{R}^2$	0.79	0.79	0.62	0.72	0.74
Clustering	Well-Time	Well-Time	Well-Time	Well-Time	Well-Time
Num. clusters	136	108	155	134	155

Table: A shale play is a geological formation where unconventional oil reserves are prevalent. Bakken and Permian shale plays cross state lines and we exclude Montana and New Mexico from the estimations, respectively.

Final lessons

- It is the largest firms that account for the strongest price-responsiveness in the sample. Access to more resources.
- We uncover a well-spacing externality. Wells spaced more than 600 feet apart respond much stronger.
- A firm-level analysis provides the same general conclusion as the well-level analysis: shale well operators respond on average positively to favourable oil price signals
- Across individual states, 7 out of 10 states exhibit a positive price response. The lack of response in CA, NM and WY may be attributed to topographic isolation and insufficient pipeline infrastructure
- The price-responsiveness in shale plays tends to be stronger than the results found for the state where the play is located.