Fracking and Structural Shifts in Oil Supply

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ABSTRACT

The adoption of hydraulic fracturing (fracking) and horizontal drilling technology substantively altered the structure of oil supply. Using disaggregate state-level data from the U.S, this paper provides empirical evidence that oil supplies are now asymmetric with respect to price changes as a result of the adoption of new production methods. The changed structure of U.S. oil supply—particularly the low supply elasticities for price declines and large supply elasticities for price increases—is consistent with the ineffectiveness of OPEC policies intended to drown fracking American producers in oil.

Keywords: Fracking, Oil Supply, OPEC

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1. INTRODUCTION

Oil producers in North Dakota, Texas, and a few other regions have helped to catapult America to its position of prominence as the world's leading producer of crude oil today. It is apparent that the level of production in America has risen rapidly since the adoption of horizontal drilling and hydraulic fracturing (fracking) production techniques (see Figure 1). Clearly the oil supply curve has shifted outward. What is not readily apparent from descriptive statistics on U.S. oil production is how the adoption of these production methods has changed the *structure* of oil supply in the U.S. "The peculiar features of the shale revolution have altered the nature of supply in critical ways. Not only are entirely new sources technologically viable, they can be brought online in tiny increments—the cost of a productive shale well is *three orders of magnitude* smaller than Arctic or deep-sea projects" (Dimitropoulos and Yatchew, 2018, pp. 683–684).[1] Recent work by Anderson et al. (2018) and Newell and Prest (2019) demonstrates—using theoretical and empirical evidence—that the primary margin of adjustment of oil supply to price changes is through increased drilling activity and production from new wells and *not* by additional production from existing wells. The analysis in this paper drills down a little deeper into this way of thinking by examining how oil supply may differ across regions using conventional technologies and regions using hydraulic fracturing production methods.

There is much anecdotal evidence about how technological innovation may have changed the cost structure of producing crude oil, particularly in tight oil formations where conventional

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[1] Dimitropoulos and Yatchew (2018) refer to the 'tiny increments' as *scalability* of the fracking production technology. Scalability is impacting not only oil markets but also the natural gas and electric power industries (Yatchew, 2019).

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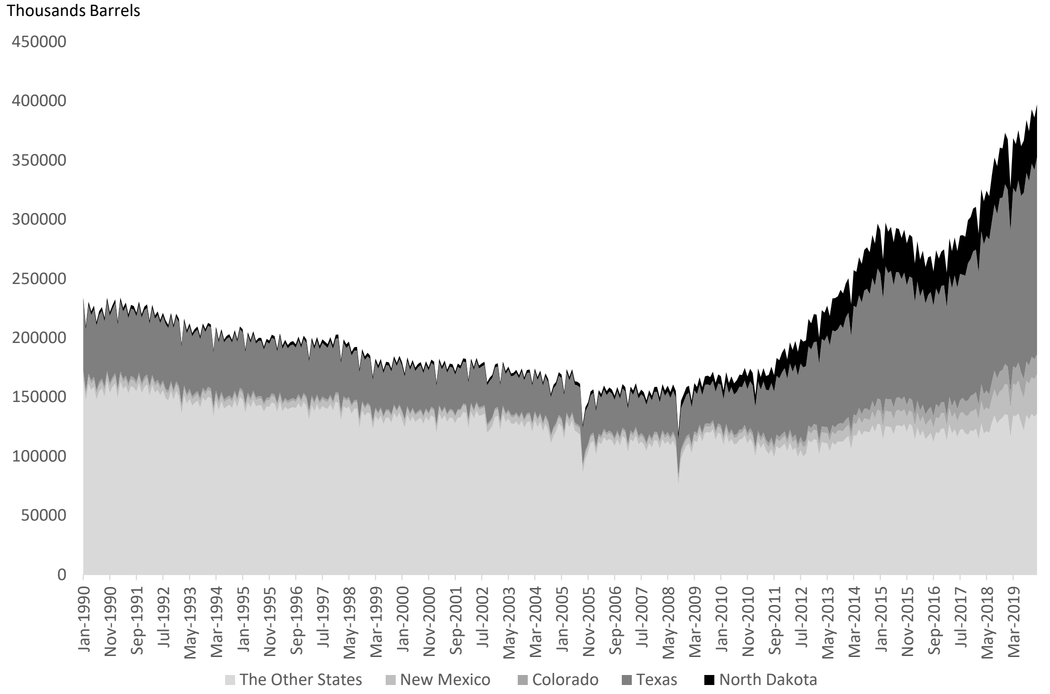
Figure 1: Composition of U.S. Crude Oil Production



Data from EIA, https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm.

production techniques were not economically feasible.[2] But a large part of the reason that hydraulic fracturing has shifted oil supply is due to the reduction in uncertainty surrounding crude oil exploration and production using this technology. Consider the discoveries of new additions to proved reserves by three channels: (i) extension of existing fields through enlargement of the production reservoir area; (ii) new reservoir discoveries in old fields; (iii) new field discoveries. The actual expansion of reserves for each channel is plotted in Figure 2. Among these three categories, new reservoir discoveries in old fields is the most uncertain outcome because it requires costly deep drilling in the search for new reservoirs. Extension is the least risky, particularly with innovations in horizontal drilling and hydraulic fracturing. From 1990 to 2008, the composition of reserves expansion by extension, new field discoveries, and new reservoir discoveries in old fields was 61%, 23% and 16%, respectively. However, since 2008 the composition of new reserves additions has changed to 87%, 7%, and 6%, respectively. The increasing contribution of extensions to new proved reserves has been driven primarily by horizontal drilling and the adoption of hydraulic fracturing. As a result, the search for new proved reserves *via* extension has become far less risky.[3] Newell et al. (2019) convincingly reason that conventional oil and gas investments resemble "trophy hunting," with

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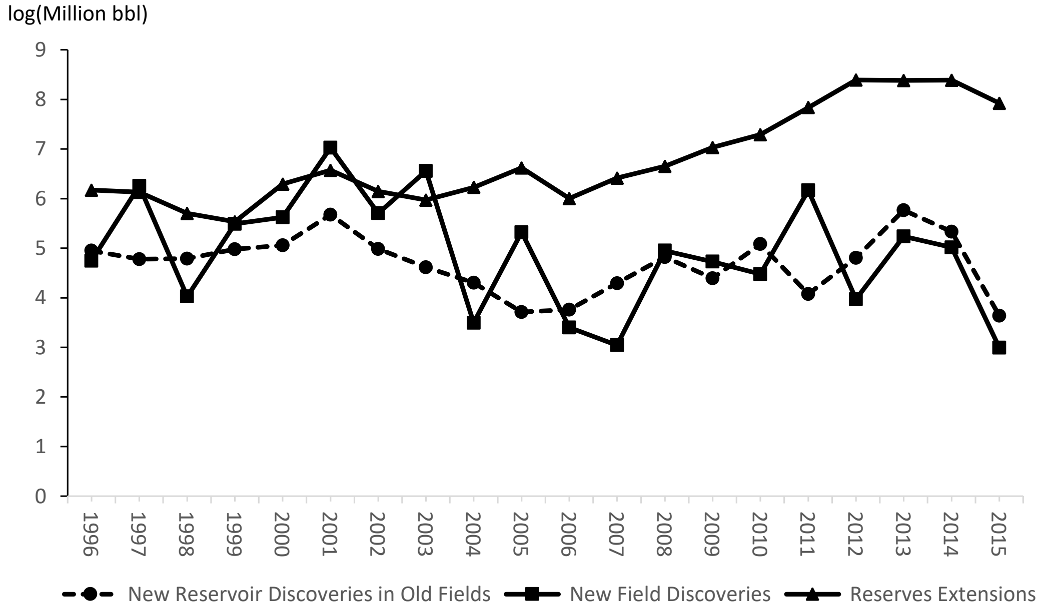
[2] Cost-reducing measures have also been implemented in conventional oil production. See, for example, "How Actual Nuts and Bolts Are Bringing Down Oil Prices," an article by Tracy Alloway in *Bloomberg Business*, September 28, 2016.

[3] This echoes Bud Brigham's remark that combining this new technology (horizontal drilling and fracking) with three-dimensional seismic mapping results in a drilling success rate of nearly 100% in the Bakken shale formations (i.e., without a dry hole) (Gold, 2014, p. 60). In contrast to the historical success rate of 10% for wildcat wells, shale production has a very low risk of failure. The adoption of fracking allows producers to raise their production from existing proved reserves rapidly in a favorable price environment.

Figure 2: Extension, New Discoveries in Old Fields, and New Field Discoveries



Data from EIA, https://www.eia.gov/dnav/pet/pet_crd_pres_dcu_NUS_a.htm.

high risks compensated by high rewards; however, modern unconventional extraction resembles a "manufacturing process" in which operators are much more certain of their production prospects.

In this paper, we provide econometric estimates of the supply relation for groupings of U.S. oil producers that differ in their use of hydraulic fracturing. We find that fracking is associated with i) supply responses that are asymmetric with respect to price increases and decreases; ii) a much larger supply response with respect to price rises than is the case for non-fracking producing regions; and iii) a faster speed of adjustment to price changes. Because shale oils account for about one-half of U.S. oil output, these attributes of supply can have important implications for the world oil market, particularly if they are the *marginal* producers. First, price increases cause a rapid increase in tight oil output, making fracking oil producers a primary beneficiary of price increases. Second, price decreases cause a much smaller decrease in tight oil output; even in a falling price environment, the decrease of tight oil output is limited.[4] The features of post-shale-boom U.S. oil supply are helpful in explaining the impotence of recent OPEC policy actions intended to elevate and stabilize the world price of crude oil after causing shale operators to exit the industry.

In the following section we set out a straightforward oil supply model that incorporates i) the possibility of asymmetries with respect to price; ii) partial adjustment of supplier behavior over time; and iii) endogenous structural change in the supply relation. In Section 3 we estimate the oil supply model as a fixed-effects panel with a possible (endogenously determined) structural break for

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[4] Kilian (2017) notes this very possibility in his study of the impact of U.S. fracking on Arab oil producers: "Even if the current low price of oil were to put shale oil producers out of business, an obvious concern would be that shale oil production is likely to resume as soon as world oil prices recover sufficiently, as long as there remains easily accessible shale oil in the ground" p. 155. Dimitropoulos and Yatchew (2018) also make the point that shale producers' rapid output expansion in response to price increases limits OPEC's effectiveness in reducing supply to elevate prices. Yatchew (2019) explains how OPEC's lowering prices by rapidly expanding output was also ineffective at forcing shale producers to exit, because shale producers responded by further reducing costs.

each region where changes in production have been driven mainly by hydraulic fracturing—North Dakota, Texas, Colorado, and New Mexico—and in all other regions as a whole; short-run production elasticities, long-run elasticities, and speeds-of-adjustment are calculated from the estimated supply relations. We then report a number of refinements and extensions to the baseline oil supply model in Section 4. We show that firms' financial management in practice is consistent with our empirical results and discuss how the asymmetry of marginal oil supplies may have severely limited OPEC's ability to manage the world oil market in Section 5. Final conclusions are summarized in Section 6.

2. OIL SUPPLY WITH STRUCTURAL CHANGE, ASYMMETRIES, AND PARTIAL ADJUSTMENT

Table 1 reports and summarizes estimates of crude oil supply elasticities reported in the scholarly literature. Of the numerous studies listed, only three yield non-negative estimates for short-run supply elasticity: 1) the model used by Hogan (1989) that was estimated on aggregate data, 2) the model of Rao (2018) estimated on California well-level data, and 3) the model of Newell and Prest (2019) for unconventional production estimated on well-level data from five U.S. States. Estimates of the elasticity of crude oil reserves with respect to price are uniformly positive.

Table 1: Summary of Crude Oil Supply and Reserves Elasticities

Crude Oil Production				
source	model type	data & sample	short run elasticity	long run elasticity
MacAvoy (1982)	static	1955–1973, U.S. aggregate	insignificant	NA
Griffin (1985)	static	1971:Q1–1982:Q3, U.S. aggregate	–0.05	NA
Griffin and Jones (1986)	cost function	1983 Texas well-level data	–1.39	NA
Hogan (1989)	dynamic*	1966–1987, U.S. aggregate	0.09	0.58
Jones (1990)	static	1971:Q1–1988:Q4, U.S. aggregate	–0.24	NA
Dahl and Yücel (1991)	static	1971–1987, U.S. aggregate	–0.08	NA
Baumeister and Peersman (2013)	Bayesian VAR	global productions	0–0.2 for 1990–2010	
Anderson et al. (2018)	static	1990:M1–2007:M12, Texas lease-level data	–0.0008	NA
Rao (2018)	static	1975:M1–1985:M12, California well-level data	0.295–0.371	NA
Newell and Prest (2019)	static†	2000:M1–2015:M12, well-level data, five states	0.12 (unconventional) –0.02 (conventional)	NA

Crude Oil Reserves				
source	model type	data & sample	short run elasticity	long run elasticity
Kaufman et al. (1994)	static	1983:Q4–1990:Q1, U.S. aggregate	0.03–0.36	NA
Dahl and Duggan (1996)	static	1986–1987, U.S. field level	1.27	NA
Farzin (2001)	dynamic	1986–1987, U.S. aggregate	0.11	0.16

*Hogan's (1989) dynamic model includes lagged production.

†Newell and Prest (2019) do not include lagged production, but do include up to three lags of prices.

The estimates vary starkly among the different studies of oil supply. A particularly interesting finding in the Newell and Prest (2019) model is that well-level unconventional oil supply has a positive supply elasticity while the elasticity for conventional oil wells is close to zero. This finding is consistent with the observation of Anderson et al. (2018) that the main margin of adjustment for oil supply is drilling activity and not additional production from existing wells.[5] For the technological reasons discussed above in Section 1, we expect the unconventional oil producing regions to have a supply structure that differs from the conventional oil producing regions.

In the following sections, we propose an oil supply modelling framework that 1) captures differences in the oil supply relation between fracking and non-fracking producing regions; 2) allows for the possibility of a structural break in the oil supply relation (motivated by the boom in shale oil production that began in 2008 as shown in Figure 1 above); and 3) allows for asymmetries in supply responses to increases and decreases in the price of oil.

2.1 Decomposing Price Changes

Gately and Huntington (2002) suggest a decomposition of price changes to estimate the asymmetric effects of price increases and decreases.[6] Following the approach of Gately and Huntington (2002), we decompose crude oil first-purchase price (p_t) in each period using the equation (1) below,

$$ln(p_t) = p_0 + prise_t + pct_t, \tag{1}$$

where $ln(p_t)$ is the logarithm of the real first purchase price of crude oil at time t; p_0 is the initial log price of crude oil; $prise_t$ denotes the cumulative increase (rises) of $\ln(p)$; and pct_t represents the cumulative decreases (cuts) of $\ln(p)$. The sample used for estimation spans January 1986–February 2019.[7] As an example of the price decomposition, the first purchase price for Texas is displayed in Figure 3.

2.2 Oil Supply Model for Shale Regions

With the price variable decomposed as set out above, we propose to estimate the price elasticity of supply for four shale-rich regions in the U.S.: North Dakota, Texas, Colorado, and New Mexico.[8] We explicitly account for structural change in supply behavior that may be associated with the adoption of hydraulic fracturing production methods. We propose a structural change model where the breakpoints are unknown and jointly estimated with the coefficients of the supply equation.[9] Specifically, consider a model with one unknown breakpoint as set out below:

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[5] In addition to the Anderson et al. (2018) and Newell and Prest (2019) papers, estimates of the response of drilling activity are reported in Brown et al. (2018).

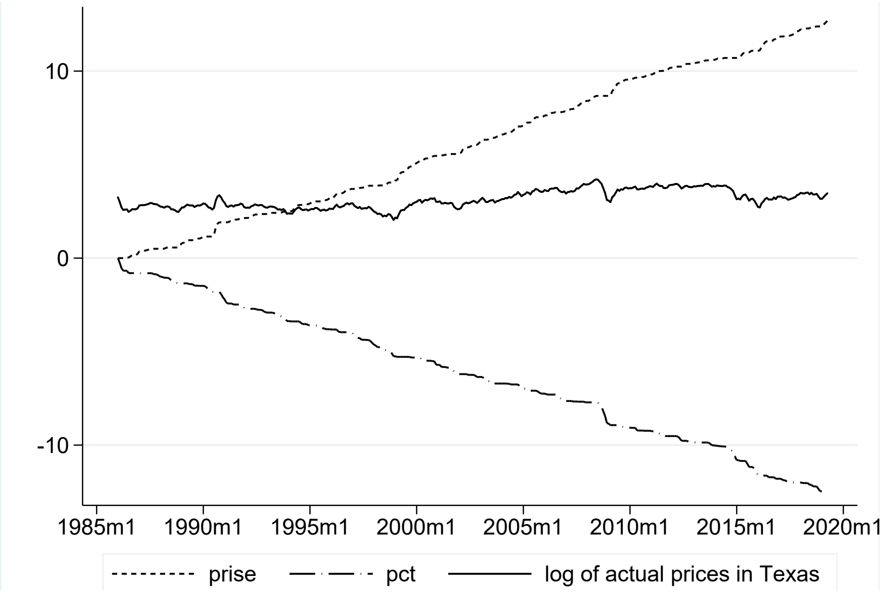
[6] Gately and Huntington's (2002) application of asymmetric price effects is applied to energy and oil demand. Supply relations may also be asymmetric; for example, the world oil model of Gately (2004) explicitly allows non-OPEC oil suppliers to have asymmetric responses with respect to price changes.

[7] With the exception of CRB commodity price indices discussed in Section 3.3, all data were obtained from the U.S. Energy Information Administration (EIA).

[8] These four states are located in major shale basins in the U.S.: Bakken (North Dakota), Permian (Texas and New Mexico), Eagle Ford (Texas), and Niborica (Colorado). By the end of 2018, these shale formations accounted for more than 85% of total shale oil production in the U.S.

[9] The estimation of structural change models was developed by Bai and Perron (Bai and Perron, 1998; Bai and Perron, 2003a; Bai and Perron, 2003b). Hansen (2001) and Perron (2006) also provide an instructive review of this literature.

Figure 3: Decomposition of TX First Purchase Prices into Cumulative Rises and Cuts



$$\begin{aligned} ln(Q_t) = \; & c + I_1(t < T)\left[\alpha_1 ln(Q_{t-1}) + \beta_1 prise_t + \gamma_1 pct_t\right] \\ & + I_2(t \geq T)\left[\alpha_2 ln(Q_{t-1}) + \beta_2 prise_t + \gamma_2 pct_t\right] + \varepsilon_t, \end{aligned} \tag{2}$$

where $ln(Q_t)$ is the log of monthly production (barrels) at time t and $ln(Q_{t-1})$ is lagged production; t is a time trend and T is the unknown date when the structural break occurs. $I_1(t < T)$ and $I_2(t \geq T)$ are two indicator functions defined as,

$$I_1(t < T) = \begin{cases} 1 & \text{if } t < T, \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$I_2(t \geq T) = \begin{cases} 1 & \text{if } t \geq T, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

In model (2) there are two regimes. The estimated coefficients α, β and γ differ between two regimes: $T_0 \leq t < T$ and $T \leq t \leq T_m$ where T_0 and T_m are the initial and final periods of the sample, respectively. The model can be extended to m breakpoints and thus with $m+1$ regimes. The least-squares estimates are obtained by minimizing the sum of squared residuals (SSR) across two regimes. We expect to find a structural change of supply behavior in each of the four shale-rich regions. As a result, we allow maximum one structural change during the sample period. As suggested by Bai and Perron (2003a), we set the trimming percentage as 15%, which implies we require at least 60 observations to fit a regime.[10] The search for the potential breaking date involves sequentially evaluating minimized SSR over two regimes for all candidate break points T. For each candidate T, the minimized SSR over two regimes are computed by applying least squares to each regime. A potential breaking date $\hat{T}$ is selected if it achieves the least minimized SSR over two regimes. Next, a

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[10] A large trimming percentage is necessary in finite samples when allowing heterogeneous error terms across regimes. A small trimming percentage, say 5%, would lead to substantial distortions in estimates (Bai and Perron, 2003a; Bai and Perron, 2003b). The minimum length of a regime consists of $0.15 \times 398 = 60$ observations, where 398 is the sample size.

Wald test is used to further confirm that the breaking date $\hat{T}$ is statistically significant. We can reject the null in favor of the model with one break if the least minimized SSR over two regimes with one break model is sufficiently smaller than the minimized SSR by using the whole sample.[11] A breaking date $\hat{T}$ is confirmed if it yields the least minimized SSR over two regimes and also rejects the null hypothesis of no structural break.

2.3 Oil Supply Model: Non-Shale Producing Regions

It is reasonable to consider whether the presence of a structural break was present in the non-shale producing regions of the U.S.; in these regions the reserves of shale oil are either absent or not fully developed. If the changes in supply behavior are driven mainly by fracking, we would *not* expect to find a similar structural change in the non-shale producing regions. To examine this possibility, we estimate a fixed-effect panel threshold model for all onshore production regions other than North Dakota, Texas, Colorado, and New Mexico.[12] The panel threshold model developed by Hansen (1999, 2000) is analogous to the structural change model. Specifically, we estimate the panel threshold model that is the analogue of equation (2):

$$\begin{aligned} ln(Q_{it}) = \quad & c + I_1(x_{it} \le \lambda)\left[\alpha_1 ln(Q_{it-1}) + \beta_1 prise_{it} + \gamma_1 pct_{it}\right] \\ & + I_2(x_{it} > \lambda)\left[\alpha_2 ln(Q_{it-1}) + \beta_2 prise_{it} + \gamma_2 pct_{it}\right] + \mu_i + \varepsilon_{it}, \end{aligned} \tag{5}$$

where μ_i is the fixed effect for region *i*, including 30 crude-oil producing states and federal offshore; x_{it} is a threshold variable and λ is a scalar. The estimated coefficients switch from α_1, β_1, and γ_1 to α_2, β_2, and γ_2 if x_{it} is larger than the the threshold λ. We set $x_{it} = t$ so that equation (5) is comparable to the structural change model (2). Similarly, the threshold λ is unknown and jointly estimated along with coefficients across the two regimes. Hansen (2000) shows the model can be estimated by the same method as the structural change model, though testing the threshold effect requires bootstrapping the distribution of test statistics. The remaining specification of estimating equation (5) is isomorphic to equation (2).

3. BASELINE EMPIRICAL RESULTS

3.1 Dates of Structural Changes

We obtain state-level oil production and the first purchase prices of crude oil from the U.S. Energy Information Administration (EIA). The sample spans from January 1986 to February 2019. The estimated dates of structural change, reported in Table 2, are as follows: March 2008 for North Dakota and March 2011 for Texas, New Mexico, and Colorado.[13] Comparing test statistics to the

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[11] There are three types of tests to confirm breaking dates: the supF type is testing the null of no structural break against $m = k$ breaks; the double maximum test is testing the null of no structural break against an unknown number of breaks with an upper bound *M*; the supF $(l+1|l)$ is testing the null of *l* breaks against $l+1$ breaks. Bai and Perron (2003a) recommend adopting the double maximum tests to determine the presence of at least one structural break. For this reason we have chosen to use the double maximum test in this study.

[12] The non-shale producing regions does not include offshore oil production.

[13] In our analysis, the dates of structural change can differ between the various shale-producing states to reflect that unconventional production methods were introduced in some states before others. The estimated dates of the structural breaks

appropriate 5% critical values, we find that in each case the null of no structural break is rejected. The evidence strongly indicates that there was a structural break of supply relations for all four states. The estimated dates of structural supply shifts in each shale-oil producing state match precisely the time when output began increasing sharply due to the introduction of hydraulic fracturing technology. North Dakota has the earliest date of structural break as Bakken was the test bed for applying fracking in oil production. Figures 4 and 5 display graphically the level of production and the estimated break points. For the other regions—those that did not adopt hydraulic fracturing—we cannot reject the null hypothesis of no structural change.

Table 2: Dates of Structural Breaks: Estimation and Testing

	North Dakota	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	26.08	13.98
estimated breaking date	March 2008	
	Texas	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	28.11	13.98
estimated breaking date	March 2011	
	New Mexico	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	17.37	13.98
estimated breaking date	March 2011	
	Colorado	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	26.08	13.98
estimated breaking date	March 2011	
	Non-Shale Producing Regions	
The null vs. alternative	F-statistic	Critical Value††
break vs. 1 break*	36.98	333.12
estimated breaking date	None	

*$p < 0.05$

† Bai and Perron (2003b)'s critical values.

†† Hansen (1999)'s bootstrap critical values.

3.2 Supply Elasticities

The estimated coefficients of the structural change model (2) for the shale-producing regions are presented in Tables 3, 4, 5, and 6. The results of the panel threshold model (5) for all other regions taken as a whole—regions that are not predominantly producing shale oil—are shown in Table 7. The estimated coefficients of pct_t and $prise_t$ can be interpreted directly as short-run supply elasticities. Because the price cut variable is a negative number, the elasticity estimate will be a positive number if falling prices cause a reduction in oil supplied. For the discussion of the elasticity estimates, we will focus on the magnitudes of the elasticities of oil supply with respect to price cuts and price rises.

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across states are broadly consistent with the date of November 2008 used by Kilian (2017) as the beginning of the shale oil boom for the U.S. as a whole.

Figure 4: Estimated Structural Breaks in Production: Texas and North Dakota

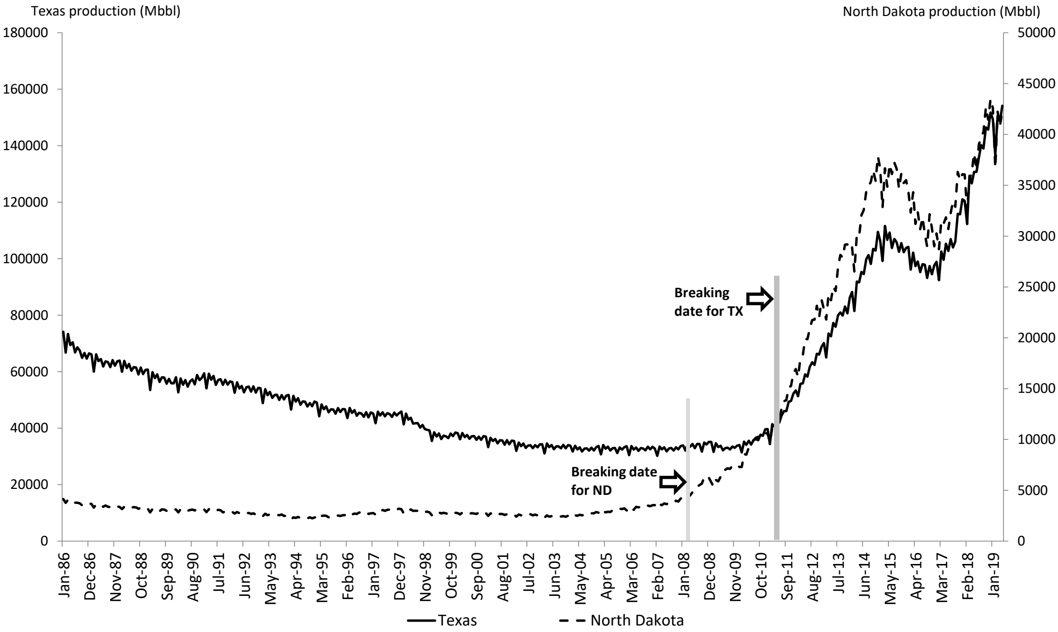
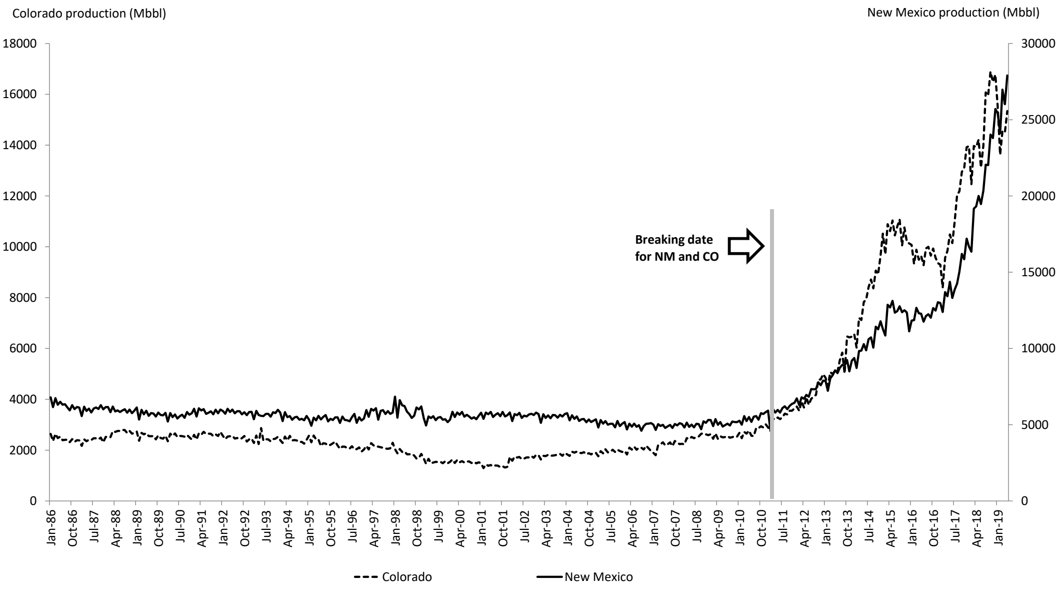


Figure 5: Estimated Structural Breaks in Production: Colorado and New Mexico



For North Dakota (Table 3), the short-run supply elasticities for price cuts and price rises—the coefficients on pct_t and $prise_t$, respectively, were nearly identical before the shale oil boom. After the widespread adoption of fracking production methods, the short-run elasticity for price rises (0.053) was about 25% higher than the short-run supply elasticity for price cuts (0.042). For Texas, the coefficient on price cuts was larger in magnitude than the coefficient on price rises prior to the shale oil boom. Since the shale oil boom, the coefficient on price cuts is not statistically different from zero and the coefficient on price rises has risen by more than three times, from 0.011 to 0.036. For New Mexico, we find that the coefficients on price rises and price cuts are not different from zero prior to the shale boom; after the shale boom the coefficient on price rises becomes positive and significant, while the coefficient on price cuts remains no different from zero. For Colorado, the coefficients on price rises and cuts were about 0.02, but became no different from zero since the shale oil boom. With the exception of Colorado, the coefficients on $prise_t$ become much larger after the structural change: Oil supply became more elastic with respect to price increases after the implementation of hydraulic fracturing production methods. For the non-shale oil producing regions taken as a whole, we cannot reject the null hypothesis of symmetry of supply responses to oil price rises and price cuts.[14]

In addition to permitting asymmetric supply adjustments with respect to price, the estimated supply model allows for adjustments over time. The coefficients α_1 and α_2 on lagged output in the supply equation represent the importance of past supply in determining future supply in the pre- and post-shale oil boom periods, respectively. The importance of past supply can most readily be interpreted as the speed of adjustment $(1-\alpha)$. For example, a low value of α means that past output is not very important in determining future supply, so $(1-\alpha)$ would indicate a high speed of adjustment. From Tables 3 through 5 it is clear that the speed of adjustment in each shale-producing region has *increased* since the beginning of the shale-oil boom.

We now estimate the long-run elasticities of supply with respect to price cuts, LRE_{pct_t} and with respect to price rises LRE_{prise_t} before and after the dates of structural change as follows:

$$LRE_{pct_{tj}} = \frac{\beta_j}{1-\alpha_j}, LRE_{prise_{tj}} = \frac{\gamma_j}{1-\alpha_j}, \tag{6}$$

where $j \in \{1,2\}$ indicates the pre- and post-shale oil boom regimes in equations (2) and (5). The estimated long-run elasticities are reported in Table 8.

For North Dakota, the (magnitude of) the long-run supply elasticity with respect to price cuts is estimated to be about 1.27, while the corresponding elasticity with respect to price rises is 1.16 after the structural break: The long-run price rise elasticity is not statistically different from the price cut elasticity since the adoption of hydraulic fracturing production methods. However,

Table 3: Estimated Results of Model (2) for North Dakota

	1986:2–2008:2	2008:3–2019:2
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.975*** (0.006)	0.967*** (0.008)
pct_t	0.011*** (0.005)	0.042*** (0.013)
$prise_t$	0.012*** (0.004)	0.053*** (0.017)
Intercept	0.204*** (0.052)	
R^2	0.997	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

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[14] From Table 7 it is clear that the magnitudes of the price cut elasticity (0.008) and price rise elasticity (–0.002) both do not differ statistically from zero.

Table 4: Estimated Results of Model (2) for Texas

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.911***	0.882***
	(0.018)	(0.023)
pct_t	0.019***	0.035
	(0.005)	(0.074)
$prise_t$	0.011***	0.036**
	(0.004)	(0.018)
Intercept	0.995***	
	(0.201)	
R^2	0.987	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 5: Estimated Results of Model (2) for New Mexico

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.858***	0.752***
	(0.040)	(0.062)
pct_t	–0.005	–0.023
	(0.008)	(0.023)
$prise_t$	–0.007	0.076**
	(0.008)	(0.098)
Intercept	1.231***	
	(0.344)	
R^2	0.977	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 6: Estimated Results of Model (2) for Colorado

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.954****	0.937***
	(0.011)	(0.018)
pct_t	0.023***	–0.003
	(0.009)	(0.015)
$prise_t$	0.021**	0.016
	(0.007)	(0.019)
Intercept	0.370***	
	(0.088)	
R^2	0.990	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

for Texas, Colorado, and New Mexico we find that the long-run elasticity for price rises is larger in magnitude than the long-run elasticity for price cuts after the structural change. In these regions, not only is the supply elasticity with respect to price rises large and statistically significant, but the supply response with respect to price cuts is not statistically different from zero since the structural

Table 7: Estimated Results of Model (5) in Non-Shale Producing Regions

Variable	Coefficient
$ln(Q_{t-1})$	0.722*** (0.182)
pct_t	0.008 (0.104)
$prise_t$	–0.002 (0.079)
R^2	0.644

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 8: Estimated Long-Run Supply Elasticities

	North Dakota	
	1986:2–2008:02	2008:3–2019:02
pct_t	0.453***	1.270***
	(0.181)	(0.480)
$prise_t$	0.467***	1.161***
	(0.175)	(0.053)
	Texas	
	1986:02–2011:02	2011:03–2019:02
pct_t	0.217***	0.031
	(0.054)	(0.112)
$prise_t$	0.120***	0.304**
	(0.050)	(0.153)
	New Mexico	
	1986:2–2011:02	2011:03–2019:02
pct_t	–0.0358	–0.094
	(0.057)	(0.094)
$prise_t$	–0.047	0.306**
	(0.051)	(0.134)
	Colorado	
	1986:02–2011:02	2011:03–2019:02
pct_t	0.507***	–0.053
	(0.202)	(0.237)
$prise_t$	0.447**	0.254
	(0.181)	(0.287)
	Non-Shale Producing Regions	
	1986:2–2019:02	
pct_t	0.035	
	(0.367)	
$prise_t$	–0.003	
	(0.302)	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
standard errors in parenthesis are computed by Delta method

break. For the non-shale oil producing regions, the supply elasticity with respect to price rises is of a much smaller magnitude (–0.003) and not statistically different zero; the supply elasticity with respect to price cuts (0.035) is also not different from zero.

3.3 Controlling for Endogenous Prices

In the supply relations estimated above, it is possible that the price variables are endogenous in the shale boom period: A random shock to production may cause a change in the price variable, resulting in a non-zero correlation between the price variable and the random disturbance in the supply equation. As a concrete example of this, Kilian (2017) reports that by mid-2014 the U.S. shale oil production boom lowered the world price of oil by about \$10 per barrel.[15] Newell and Prest (2019) note that estimations for oil supply have generally not instrumented for price because incremental output, particularly from the U.S., has been small relative to world oil output. However, since the shale oil boom in America, it seems less reasonable to treat prices as exogenous. To account for possible endogeneity of the price variable since the fracking revolution, we use commodity indicies as instruments for oil prices in the estimation of the supply equations as suggested by Newell and Prest (2019).[16] Baumeister and Kilian (2012) show that Commodity Research Bureau (CRB) indices are good predictors of crude oil prices because raw commodities share the same common demand factor for industrial production as crude oil. We obtain the CRB commodity indices from Bloomberg. We then used the lagged 3–6-month indexes in the metals sector as instruments for estimating oil supply.[17]

For each region, we split the sample using the estimated dates of structural change reported in Table 2. We then re-estimated the supply equations using the GMM estimator for the post-shale sub-sample using commodity indices as instruments for current prices. The model specification for the other regions remains a fixed-effects panel model. Tables 9–13 present the estimated results for each of the shale-producing regions and the non-shale producing regions.[18] The coefficient estimates of β_{prise} and β_{pct} in those tables results represent the short-run supply elasticities with respect to price increases and decreases, respectively. Table 14 reports the corresponding long-run elasticities. The supply elasticity results reported in Section 3.2 appear to become sharper after controlling for the potential endogeneity of the price variable since the boom in shale oil production: The results from the GMM estimations more strongly support the conclusion that the structure of oil supply has changed in conjunction with the adoption of horizontal drilling and hydraulic fracturing production methods. Since the structural break occurred in the shale oil producing regions, the supply response to price changes has become increasingly asymmetric: The magnitude of supply elasticities for price rises is much larger than the corresponding elasticity for price cuts. We also find that the magnitude of the short-run supply response to price rises has increased in each of the four shale-producing

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[15] Specifically, Kilian (2017) uses a structural VAR to show that the *cumulative* price impact of the U.S. shale oil boom beginning in 2008 was about \$10 per barrel in 2014 for Brent blend. This is *not* the contemporaneous price impact of monthly shale oil production.

[16] Using lagged prices as instruments for their current values, as is common practice, would be inappropriate in this model because lagged prices are correlated with lagged production. The required exclusion restriction is violated by construction.

[17] Bloomberg reports three types of CRB indices: Overall, raw industrial materials, and metals. The first two indices may include commodities that relate to oil and gas production. Therefore, we use the metals indexes as our instruments. The set of instruments can serve as a demand factor to identify the supply relation for crude oil (Newell and Prest, 2019).

[18] The tables also report the F-statistic for the first-stage regressions and the p-values for the Hansen J test of overidentifying restrictions. These diagnostics support the use of CRB indices as instruments for the first purchase price of crude oil in the post-shale boom period.

Table 9: Estimated Results of IV Model for North Dakota

	1986:2–2008:2	2008:3–2019:2
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.975***	0.960***
	(0.006)	(0.006)
pct_t	0.011***	0.047***
	(0.005)	(0.013)
$prise_t$	0.012***	0.065***
	(0.004)	(0.017)
Intercept	0.204***	
	(0.052)	
F-stat, First Stage Regression		6559.224
p-value Hansen J Test		0.87

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
robust standard errors in parenthesis

Table 10: Estimated Results of IV Model for Texas

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.911***	0.874***
	(0.018)	(0.008)
pct_t	0.019***	0.005
	(0.005)	(0.019)
$prise_t$	0.011***	0.045*
	(0.004)	(0.025)
Intercept	0.995***	
	(0.201)	
F-stat, First Stage Regression		1390.661
p-value Hansen J Test		0.488

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parenthesis

Table 11: Estimated Results of IV Model for New Mexico

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.858***	0.721**
	(0.040)	(0.003)
pct_t	–0.005	–0.011
	(0.008)	(0.032)
$prise_t$	–0.007	0.114**
	(0.008)	(0.049)
Intercept	1.231***	
	(0.344)	
F-stat, First Stage Regression		1490.184
p-value Hansen J Test		0.138

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parenthesis

regions since the structural break. The long-run supply is also asymmetric with respect to price cuts and price rises in each of the four shale-producing regions since the structural break. The magnitude of the long-run supply elasticity with respect to price rises has increased in North Dakota, Texas, and New Mexico; only in Colorado is there no statistically significant increase in the long-run supply

Table 12: Estimated Results of IV Model for Colorado

	1986:2–2011:02	2011:03–2019:02
Variable	Coefficient	Coefficient
$ln(Q_{t-1})$	0.954****	0.914***
	(0.011)	(0.016)
pct_t	0.023***	–0.003
	(0.009)	(0.017)
$prise_t$	0.021**	0.035*
	(0.007)	(0.022)
Intercept	0.370***	
	(0.088)	
F-stat, First Stage Regression		1775.047
p-value Hansen J Test		0.878

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parenthesis

Table 13: Estimated Results of IV Model for Non-Shale Producing Regions

Variable	Coefficient
$ln(Q_{t-1})$	0.709***
	(0.047)
pct_t	0.0182
	(0.047)
$prise_t$	–0.020
	(0.040)
Intercept	3.465***
	(0.572)
F-stat, First Stage Regression	938.108
p-value Hansen J Test	0.864

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parenthesis

elasticity with respect to price rises. For the non-shale producing regions, we cannot reject that supply response is symmetric with respect to price rises and price cuts; moreover, the supply elasticities are statistically no different from zero in the non-shale producing regions.

4. REFINEMENTS TO THE ECONOMETRIC ANALYSIS OF OIL SUPPLY

In this section we provide a number of extensions to the baseline empirical analysis reported above. In particular, we i) incorporate lagged oil prices into the baseline oil supply model; ii) estimate supply elasticities for the shale regions as a whole, aggregating the four shale-rich regions together; and iii) test for structural breaks between early and late shale oil booms.

4.1 Including Lagged Prices in Oil Supply Model

Since previous drilling decisions may affect current oil production, we augment the baseline model to include one-month lagged prices as additional explanatory variables.[19] The structural change model with one unknown breakpoint and lagged one-month prices is then:

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[19] We also tried lagged two-month and three-month prices in the model. But using information criteria metrics (AIC, BIC, etc.), lagged one-month prices yield best results.

Table 14: Estimated Long-Run Supply Elasticities from IV Estimations

	North Dakota	
	1986:2–2008:02	2008:3–2019:02
pct_t	0.453***	1.171***
	(0.181)	(0.247)
$prise_t$	0.467***	1.613***
	(0.175)	(0.256)
	Texas	
	1986:02–2011:02	2011:03–2019:02
pct_t	0.217***	0.045
	(0.054)	(0.149)
$prise_t$	0.120***	0.363**
	(0.050)	(0.180)
	New Mexico	
	1986:2–2011:02	2011:03–2019:02
pct_t	–0.0358	–0.039
	(0.057)	(0.117)
$prise_t$	–0.047	0.409***
	(0.051)	(0.140)
	Colorado	
	1986:02–2011:02	2011:03–2019:02
pct_t	0.507***	–0.034
	(0.202)	(0.198)
$prise_t$	0.447**	0.410**
	(0.181)	(0.209)
	Non-Shale Producing Regions	
	1986:2–2019:02	
pct_t	0.063	
	(0.157)	
$prise_t$	–0.067	
	(0.143)	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
standard errors in parenthesis are computed by Delta method

$$\begin{aligned} ln(Q_t) = \quad & c + I_1(t < T)\left[\alpha_1 ln(Q_{t-1}) + \sum_{j=0}^{1}\beta_{1j}(prise_{t-j}) + \sum_{j=0}^{1}\gamma_{1j}(pct_{t-j})\right] \\ & + I_2(t \geq T)\left[\alpha_2 lnQ_{t-1} + \sum_{j=0}^{1}\beta_{2j}(prise_{t-j}) + \sum_{j=0}^{1}\gamma_{2j}(pct_{t-j})\right] + \varepsilon_t, \end{aligned} \tag{7}$$

where $ln(Q_t)$ is the log of monthly production (barrels) at time t and $ln(Q_{t-1})$ is lagged production; t is a time trend and T is the unknown date when the structural break occurs. $I_1(t < T)$ and $I_2(t \geq T)$ are two indicator functions as defined in section 2.2. The estimation procedure is identical to what we have done in previous sections.[20]

For the other non-shale regions, we estimate a fixed-effect panel threshold model with one-month lagged prices as equation (8) below:

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[20] We also estimate a set of time-series threshold regressions for each shale region, which yields the same estimated coefficients as the structural change model of equation (7).

$$\begin{aligned} ln(Q_{it}) = \quad & I_1(t \le \lambda)\left[\alpha_1 ln(Q_{it-1}) + \sum_{j=0}^{1}\beta_{1j}(prise_{t-j}) + \sum_{j=0}^{1}\gamma_{1j}(pct_{t-j})\right] \\ & + I_2(t > \lambda)\left[\alpha_2 ln(Q_{it-1}) + \sum_{j=0}^{1}\beta_{2j}(prise_{t-j}) + \sum_{j=0}^{1}\gamma_{2j}(pct_{t-j})\right] + \mu_i + \varepsilon_{it}, \end{aligned} \tag{8}$$

where μ_i is the fixed effect for region i, including non-shale oil producing states and federal offshore; t is the threshold variable and λ is a scalar. The estimated coefficients switch from α_{1j}, β_{1j}, and γ_{1j} to α_{2j}, β_{2j}, and γ_{2j} if t is larger than the threshold λ.

The estimated dates of structural change, reported in Table 15, are as follows: March 2008 for North Dakota, March 2011 for Texas, New Mexico, and Colorado. Again, we reject the null hypothesis that there is a structural change found for the non-shale regions.

Table 15: Dates of Structural Breaks: Estimation and Testing

	North Dakota	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	45.15	18.23
estimated breaking date	March 2008	
	Texas	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	30.00	18.23
estimated breaking date	March 2011	
	New Mexico	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	19.16	18.23
estimated breaking date	March 2011	
	Colorado	
The null vs. alternative	F-statistic	Critical Value†
break vs. 1 break*	34.73	18.23
estimated breaking date	March 2011	
	The other regions	
The null vs. alternative	F-statistic	Critical Value††
break vs. 1 break*	64.05	98.23
estimated breaking date	None	

* $p < 0.05$

† Bai and Perron (2003b)'s critical values

†† Hansen (1999)'s bootstrap critical values

Following Newell and Prest (2019), we compute the short-run elasticities as the cumulative responses of oil production with respect to current and lagged prices. Specifically, the short-run elasticities from equations (7) or (8) are,

$$SRE_{prise_i} = \beta_{i0} + \beta_{i1}, SRE_{pct_i} = \gamma_{i0} + \gamma_{i1}, \tag{9}$$

where β_{i0} and β_{i1} are estimated coefficients of $prise_t$ and $prise_{t-1}$, γ_{i0} and γ_{i1} are estimated coefficients of pct_t and pct_{t-1}, and $i \in \{1,2\}$ indicates the pre- and post- shale oil boom regimes. We compute the long-run elasticities of supply with respect to price cuts, LRE_{pct_t} and with respect to price rises LRE_{prise_t} before and after the dates of structural change as follows:

$$LRE_{pct_i} = \frac{SRE_{pct_i}}{1-\alpha_i}, LRE_{prise_i} = \frac{SRE_{prise_i}}{1-\alpha_i}. \tag{10}$$

Finally, to account for the possibility of endogenous price variables since the shale boom, we apply the lagged metal commodity price as instruments. For each region, coefficients are estimated using IV-GMM for post-shale-boom sub-samples of the data. The short-run and long-run elasticities are presented in Tables 16 and 17.[21]

4.2 Estimating Elasticities for the Shale Regions as a Whole

In this section, we estimate a fixed-effect panel threshold model for the four shale-rich regions as a whole. The estimated results with and without using IV are presented in Tables 18 and

Table 16: Estimated Short-Run Supply Elasticities using IV

	North Dakota	
	1986:2–2008:2	2008:3–2019:2
pct_t	0.011	0.094***
	(0.011)	(0.025)
$prise_t$	0.012	0.118**
	(0.010)	(0.035)
	Texas	
	1986:2–2011:2	2011:3–2019:2
pct_t	0.020*	0.143**
	(0.010)	(0.069)
$prise_t$	0.011	0.219**
	(0.009)	(0.106)
	New Mexico	
	1986:2–2011:2	2011:3–2019:2
pct_t	–0.004	0.098**
	(0.013)	(0.044)
$prise_t$	–0.016	0.193**
	(0.029)	(0.085)
	Colorado	
	1986:2–2011:2	2011:3–2019:2
pct_t	0.028**	0.096**
	(0.014)	(0.026)
$prise_t$	0.025**	0.170**
	(0.012)	(0.071)
	The other regions	
	1986:2–2019:2	
pct_t	0.044***	
	(0.012)	
$prise_t$	0.035***	
	(0.010)	

$^* p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$
Standard errors in parentheses are computed by Delta method

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[21] The estimated regression results for each region, which are not directly meaningful, are shown in Tables 26–30 of the Appendix, available online.

Table 17: Estimated Long-Run Supply Elasticities using IV

	North Dakota	
	1986:2–2008:02	2008:3–2019:2
pct_t	0.478	3.052***
	(0.483)	(0.950)
$prise_t$	0.498	3.821***
	(0.443)	(0.931)
	Texas	
	1986:2–2011:2	2011:3–2019:2
pct_t	0.225**	1.601***
	(0.113)	(0.253)
$prise_t$	0.125	2.454***
	(0.099)	(0.251)
	New Mexico	
	1986:2–2011:2	2011:3–2019:02
pct_t	–0.026	0.740***
	(0.092)	(0.168)
$prise_t$	–0.040	1.454***
	(0.081)	(0.137)
	Colorado	
	1986:2–2011:2	2011:3–2019:2
pct_t	0.627*	0.945***
	(0.329)	(0.301)
$prise_t$	0.576**	1.677***
	(0.292)	(0.285)
	The other regions	
	1986:2–2019:2	
pct_t	0.427***	
	(0.103)	
$prise_t$	0.339***	
	(0.091)	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Standard errors in parentheses are computed by Delta method

19, respectively. The estimated threshold (breaking point) is March 2008, when fracking expanded rapidly in North Dakota. Estimated short-run and long-run elasticities are reported in Table 20. The elasticities for the post-shale period (2008:3 to 2019:2) are re-estimated using an IV-GMM estimator and reported in Table 21. For the shale-producing regions, the difference between short-run and long-run elasticities with respect to price cuts and increases are *not* statistically different from zero before March 2008. However, the short-run and long-run elasticities with respect to increases become larger than for price cuts since the shale boom began.

4.3 Testing Structural Breaks between Early and Late Shale Booms

In this section, we extend our analysis on testing for structural breaks in oil supply. We are interested in how oil supply in the U.S. has evolved since fracking began dominating oil production. Does the oil supply elasticity in the U.S. becomes more asymmetric with the recent development of hydraulic fracturing? Or do supply elasticities revert back to symmetric behavior as technological

Table 18: Panel Threshold Model for Four Shale Regions

	1986:1–2008:2	2008:3–2019:2
$ln(Q_{it-1})$	0.990***	0.981***
	(0.002)	(0.002)
pct_{it}	–0.047**	–0.056***
	(0.012)	(0.007)
$prise_{it}$	0.070***	0.161***
	(0.009)	(0.008)
pct_{it-1}	0.052**	0.087***
	(0.010)	(0.011)
$prise_{it-1}$	–0.066***	–0.121***
	(0.011)	(0.019)
Constant	0.085**	
	(0.023)	
N	1588	
R^2	0.993	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 19: IV Panel Threshold Model for Four Shale Regions

	1986:1–2008:2	2008:3–2019:2
$ln(Q_{it-1})$	0.990***	0.930***
	(0.002)	(0.031)
pct_{it}	–0.047**	–0.369***
	(0.012)	(0.320)
$prise_{it}$	0.070***	0.434***
	(0.009)	(0.233)
pct_{it-1}	0.052**	0.438***
	(0.010)	(0.320)
$prise_{it-1}$	–0.066***	–0.317***
	(0.011)	(0.210)
F stats of First Stage Regression	44.14	
P value of Hansen J statistics	0.29	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

advances in unconventional production methods and producers' learning curve flatten? To answer these questions, we estimate a fixed-effect panel threshold model by combining the four shale-rich regions for the post-shale period (2008:03–2019:02).[22] The estimated results with and without using IV are presented in Tables 22 and 23 where a structural break point is found at June 2011 in both specifications. The corresponding elasticities with and without using IV are reported in Tables 24 and 25.

From Tables 24 and 25, we find that the elasticities with respect to price increases are only slightly larger than the elasticities with respect to price cuts during the early shale boom (March 2008-June 2011) (see the first and third columns of Tables 24 and 25). However, the elasticities with respect to price increases become much larger than the elasticities with respect to price cuts during the more recent shale boom period (July 2011-February 2019). This implies that with improving

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[22] For the sample period March 2008–February 2019 we cannot estimate a set of threshold or breaking-point models for each shale-rich region separately because of the relatively small sample size.

Table 20: Short-run and Long-run Elasticities: Panel Threshold Model for Four Shale Regions

	Short-Run Elasticities		Long-Run Elasticities	
	1986:2–2008:2	2008:3–2019:2	1986:2–2008:2	2008:3–2019:2
pct_{it}	0.005**	0.032***	0.477*	1.672**
	(0.002)	(0.012)	(0.287)	(0.796)
$prise_{it}$	0.005**	0.041***	0.481	2.142**
	(0.002)	(0.012)	(0.314)	(0.836)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 21: Short-run and Long-run Elasticities: IV Panel Threshold Model for Four Shale Regions

	Short-Run Elasticities		Long-Run Elasticities	
	1986:2–2008:2	2008:3–2019:2	1986:2–2008:2	2008:3–2019:2
pct_{it}	0.005**	0.069***	0.477*	0.993*
	(0.002)	(0.022)	(0.287)	(0.559)
$prise_{it}$	0.005**	0.116***	0.481	1.674**
	(0.002)	(0.029)	(0.314)	(0.653)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 22: The Estimated Results of a Panel Threshold Model Since the Shale Boom

	2008:3–2011:6	2011:7–2019:2
$ln(Q_{it-1})$	0.941***	0.944***
	(0.009)	(0.010)
pct_{it}	–0.157**	–0.057
	(0.047)	(0.046)
$prise_{it}$	0.515***	0.029
	(0.048)	(0.043)
pct_{it-1}	0.216**	0.087
	(0.042)	(0.049)
$prise_{it-1}$	–0.436***	0.024
	(0.048)	(0.037)
Intercept	0.306***	
	(0.044)	
N	528	
R^2	0.991	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

technology, the supply elasticity becomes more asymmetric.[23] The asymmetry is more pronounced for long-run elasticities: The last columns of Tables 24 and 25 show that the long-run elasticities with respect to price increases are nearly doubled relative to price cut elasticities. The magnitude of elasticities in the late shale boom (July 2011-February 2019) is reduced compared to early shale

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[23] This empirical finding is consistent with industry reports that low prices stimulated cost reductions that spurred increased output. See, for example, "Fracking 2.0: Shale Drillers Pioneer New Ways to Profit in Era of Cheap Oil" *Wall Street Journal*, March 30, 2017. https://www.wsj.com/articles/fracking-2-0-shale-drillers-pioneer-new-ways-to-profit-in-era-of-cheap-oil-1490894501 (accessed January 5, 2020).

Table 23: The Estimated Results of a Panel Threshold Model Since the Shale Boom by Using IV

	2008:3–2011:6	2011:7–2019:2
$ln(Q_{it-1})$	0.930***	0.931***
	(0.008)	(0.008)
pct_{it}	–0.340**	–0.035
	(0.088)	(0.059)
$prise_{it}$	1.048***	–0.389**
	(0.128)	(0.117)
pct_{it-1}	0.455**	0.063
	(0.096)	(0.081)
$prise_{it-1}$	–0.908***	0.454**
	(0.114)	(0.096)
Intercept	0.298***	
	(0.039)	
N	528	
R^2	0.991	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 24: The Estimated Short-run and Long-run Elasticities of a Panel Threshold Model Since the Shale Boom

	Short-run Elasticity		Long-run Elasticity	
	2008:2–2011:6	2011:7–2019:2	2008:2–2011:6	2011:7–2019:2
pct_{it}	0.059***	0.030***	0.993***	0.531***
	(0.007)	(0.006)	(0.238)	(0.144)
$prise_{it}$	0.079***	0.052***	1.323***	0.939***
	(0.005)	(0.008)	(0.181)	(0.082)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

Table 25: The Estimated Short-run and Long-run Elasticities of a Panel Threshold Model Since the Shale Boom by Using IV

	Short-run Elasticity		Long-run Elasticity	
	2008:2–2011:6	2011:7–2019:2	2008:2–2011:6	2011:7–2019:2
pct_{it}	0.116***	0.028	1.655***	0.404
	(0.009)	(0.023)	(0.166)	(0.338)
$prise_{it}$	0.141***	0.065***	2.007***	0.935***
	(0.015)	(0.022)	(0.177)	(0.337)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Robust standard errors in parentheses

boom period (March 2008-June 2011). To sum this up, continuing advances in fracking technology are associated with oil supply in U.S. shale-rich regions becoming more asymmetric, though the magnitude of supply responses is decreasing.

5. FINANCIAL ANALYSIS AND OVERALL DISCUSSION

This section presents a descriptive financial analysis for U.S. shale oil firms for the period of 2010Q1–2019Q4. The purpose of this section is to determine if financial management in practice is consistent with the asymmetric aggregate supply behavior evidenced in the previous sections.[24] We focus on five major publicly-listed energy firms specializing in tight oil extraction within the U.S. The five listed companies include Chesapeake Energy, Continental Resources, EOG Resources, Pioneer Natural Resources, and Whiting Petroleum.[25] We exclude vertically integrated oil producers, specifically tight oil producers owning downstream refining businesses, because we can only obtain financials for the entire business entity and not separately for the tight oil producing divisions of these companies. All the five included companies specialized in tight oil production as their core business. Data for the financial analysis were obtained from the WRDS database. We then proceed to flesh out the implications of asymmetries in unconventional oil supply on the comparative statics of world oil markets, focusing specifically on OPEC's effectiveness.

5.1 Capital Expenditure

Figure 6 plots capital expenditures (capex) for five shale oil companies from 2010Q1 to 2019Q4. All five companies experienced large reductions in capital expenditures during the 2014–2015 oil price crash, but most of them have either recovered their capital expenditures with a lower pace or maintained low levels of capex since 2016.

5.2 Operating Income

Figures 7 and 8 display operating incomes before and after depreciation, respectively. With the single exception of Continental Resources, all the companies experienced a large reduction in operating incomes during the 2014–2015 period, but have recovered since 2016. Since the first quarter of 2019, the operating incomes of a few companies have approached historical highs. This is partly because the WTI price exceeded $ 60 per barrel from late 2018 until the end of 2019 and partly because major shale producers have significantly improved productivity through investments in water handling infrastructure, sand sourcing, pad drilling, and upsized fracking completions. Innovations and knowledge disseminated across shale operators over time, driving incremental productivity gains sector-wide (Collins and Medlock, 2017).

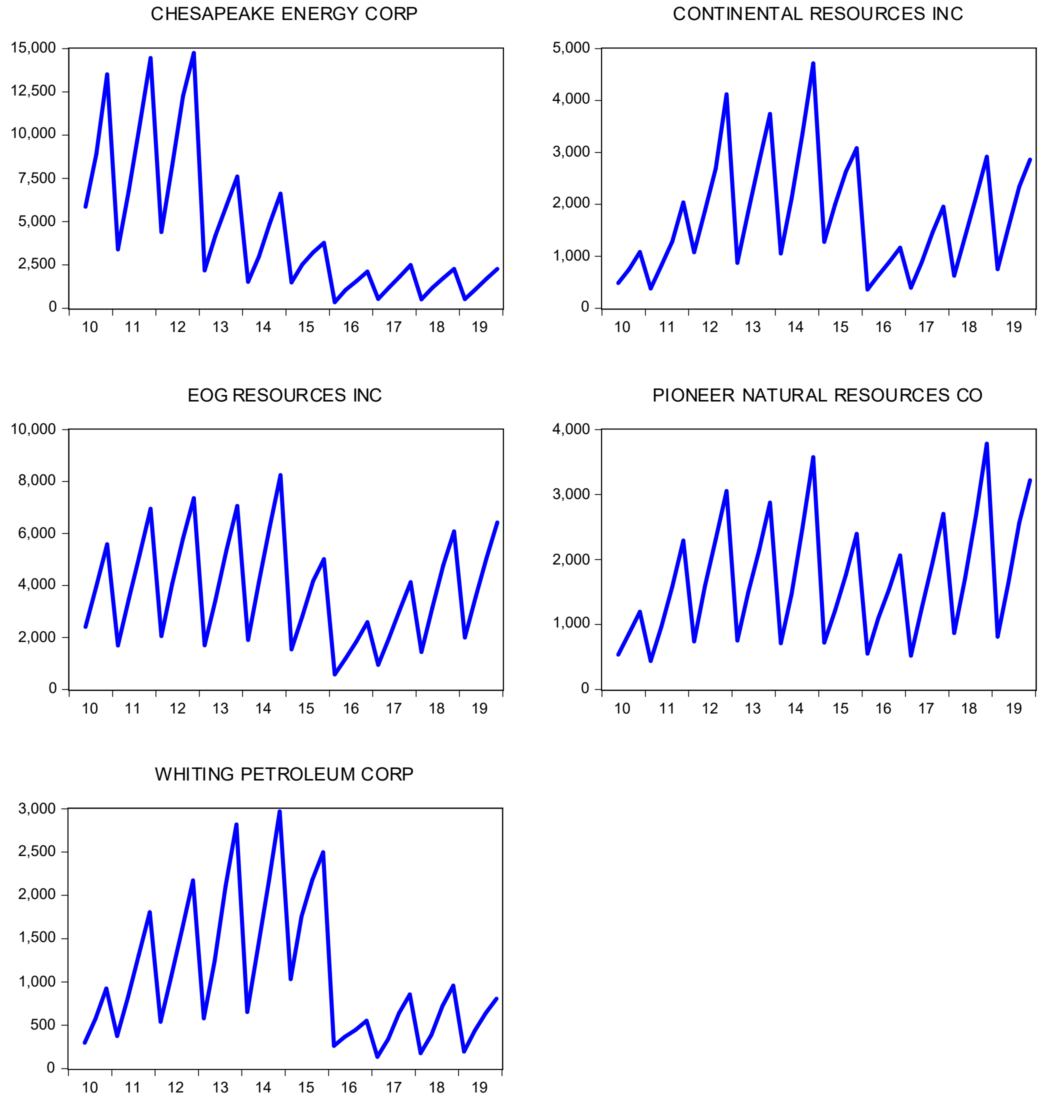
5.3 Cash Flow

We focus on three metrics of cash flow conditions: cash and short-term investment, working capital, and cash flow from operating activities after capex. Figure 9 plots the trend of cash and short-term investment for the five shale oil companies. It appears that most companies increased their cash positions during the 2014–2015 period due to a deteriorating investment outlook. A similar scenario holds for the companies' working capital (see Figure 10). Working capital—often referred to as "cash in barrel" in oil patch jargon—is critical to firms' liquidity in the face of short-term oil price fluctuations. With the single exception of Continental Resources, all the companies increased their working capital during the 2014–2015 period. Since 2016, the firms' working capital either gradually declined or has been maintained at lower levels.

[24] We are indebted to a referee for insisting that we perform a financial analysis to either confirm or refute the econometric analysis of oil supply.

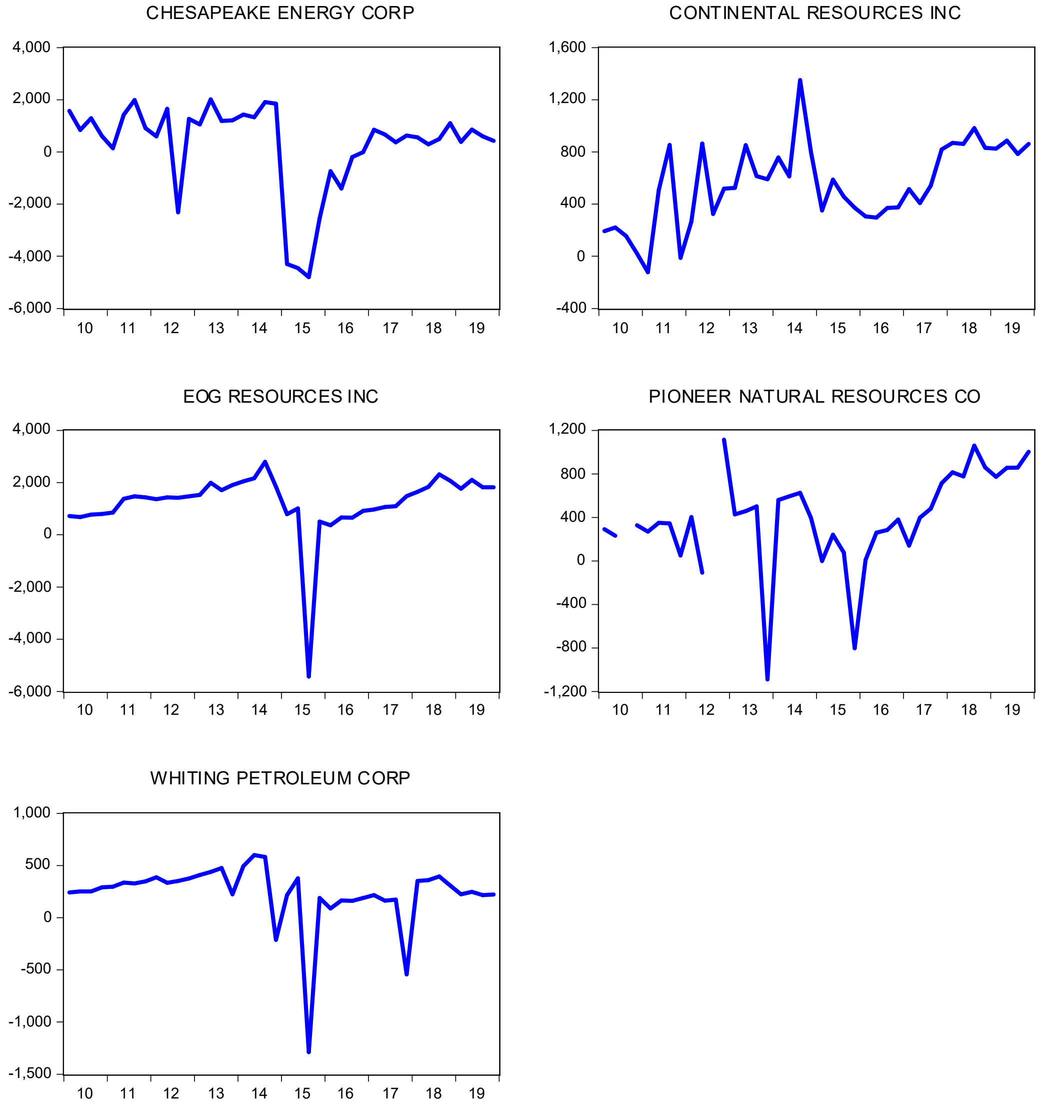
[25] We discuss the bankruptcies of Whiting Petroleum in April 2020 and Chesapeake Energy in June 2020 in Sectio 5.6 below. The financial analysis presented in this subsection is intended to correspond to the oil supply estimations of the previous two sections.

Figure 6: Capital Expenditures of Five Shale Oil Companies (Millions USD)



Finally, Figure 11 presents cash flow after capex for the five shale oil companies. This variable measures a firm's "free cash flow"—the amount of cash generated by a company's operating activity net of capital expenditures—and is crucial for a firm's financial health and future operating activity. Positive free cash flow enables firms to expand the business, reduce debt, or reward shareholders. In contrast, with negative cash flows, companies must rely on external sources to finance operations. Without additional funding and any debt refinancing, capex would have to be cut. For the past decade, most independent shale oil companies experienced negative cash flows. However, beginning in the first and second quarters of 2019, these shale companies have generated positive free cash flows (see Figure 11). The slight increase in the firms' operating incomes (see Figures 7 and 8 above), coupled with firms' efforts to maintain low capex (see Figure 6), leads to a small surplus of net operating cash flow at late 2018 and early 2019.

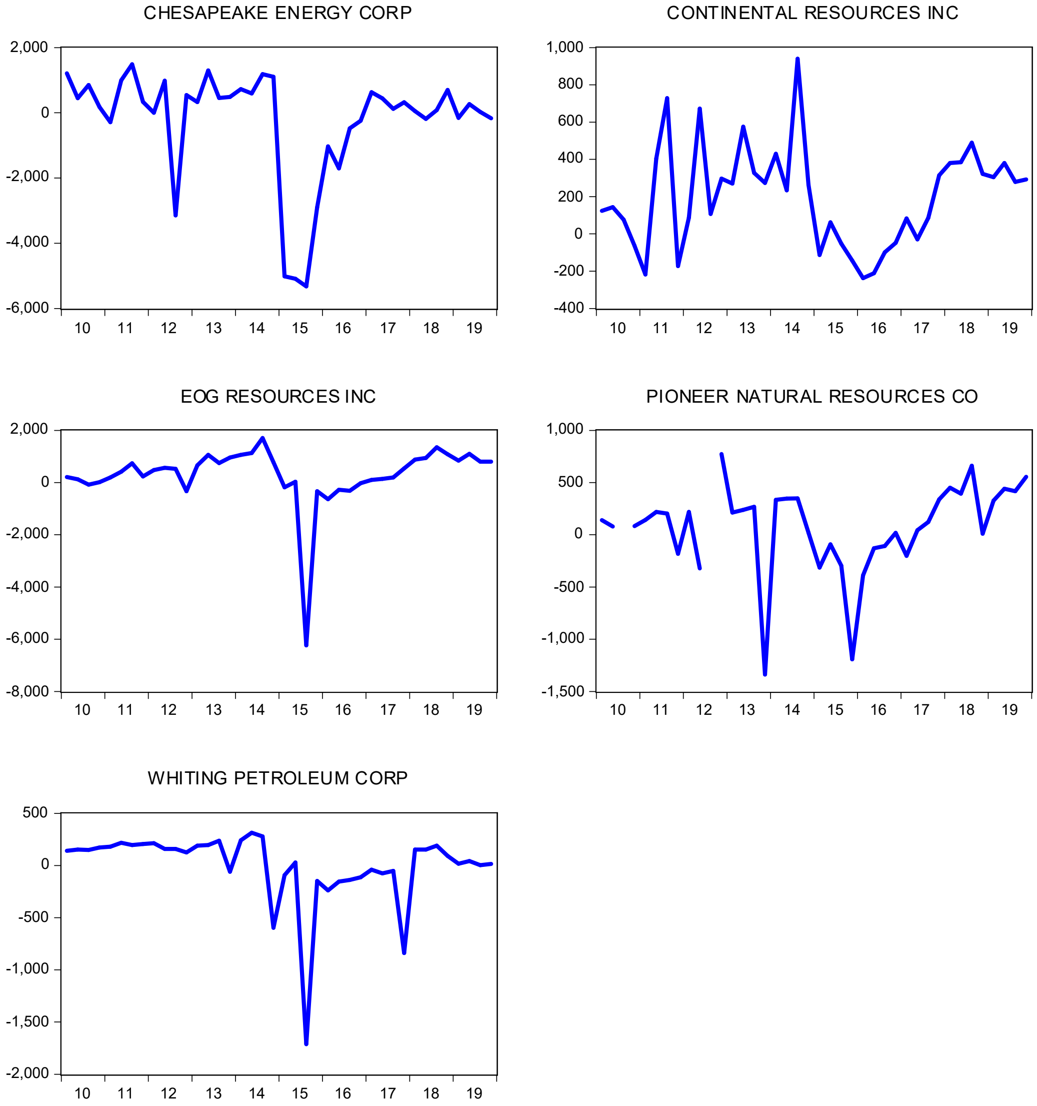
Figure 7: Operating Incomes before Depreciation of Five Shale Oil Companies (Million USD)



5.4 Financial Performance and Oil Supply Elasticities

The financial analysis above reveals how U.S. shale oil firms have managed their financial conditions under conditions of oil price volatility. These results are consistent with asymmetric supply elasticities for tight oil. When oil prices decrease, producers reduce their capital expenditures, hold cash positions, and may face negative free cash flows or operating incomes. As a result of negative free cash flows, producers reduce the pace of drilling new prospects. However, they have a limited ability to adjust the production in wells that have already been drilled (Brown et al., 2017, Anderson et al., 2018, Newell and Prest, 2019). Through this mechanism, aggregate supply elasticities with respect to price decreases are low because a large amount of drilled prospects have been accumulated since the shale boom.

Figure 8: Operating Incomes after Depreciation of Five Shale Oil Companies (Million USD)



In contrast, when crude oil prices recover, the firms increase their capital expenditures (but maintain them at relatively low levels) and may generate positive free cash flows, as happened in the first two quarters of 2019. As a consequence, firms can finance new drilling activities.[26] Because of improving drilling productivity and very large initial production from newly drilled shale wells, we observe a large price elasticity with respect to price recoveries in terms of aggregate supply behavior.

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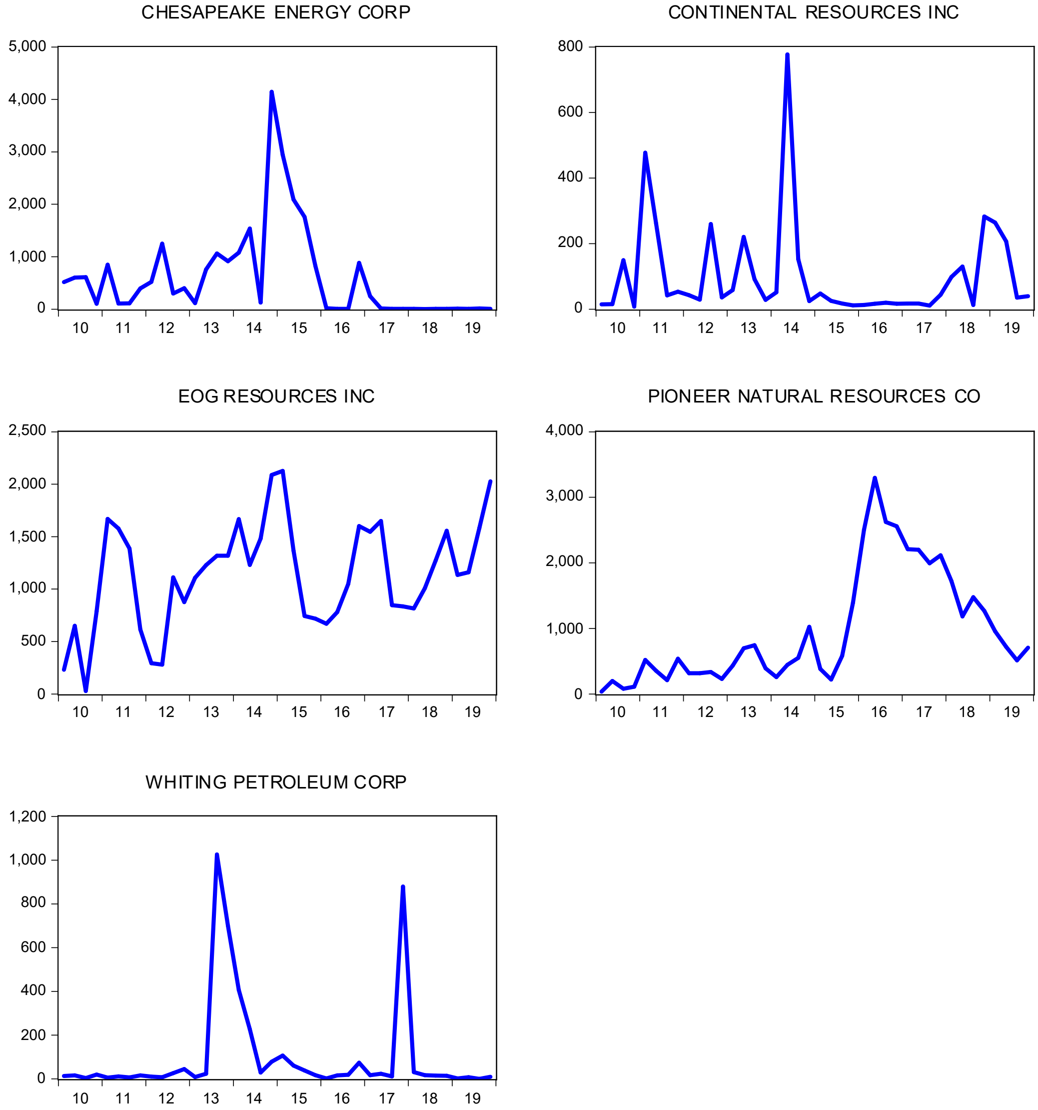
[26] New drilling activities may not be limited to drilling new wells. It also includes exploiting production from previously drilled and uncompleted wells (DUC). The shale oil production from DUCs can come online and scale up as fast as 2–3 weeks in a favorable price environment (Collins and Medlock, 2017).

Figure 9: Cash and short-run Investments of Five Shale Oil Companies (Million USD)

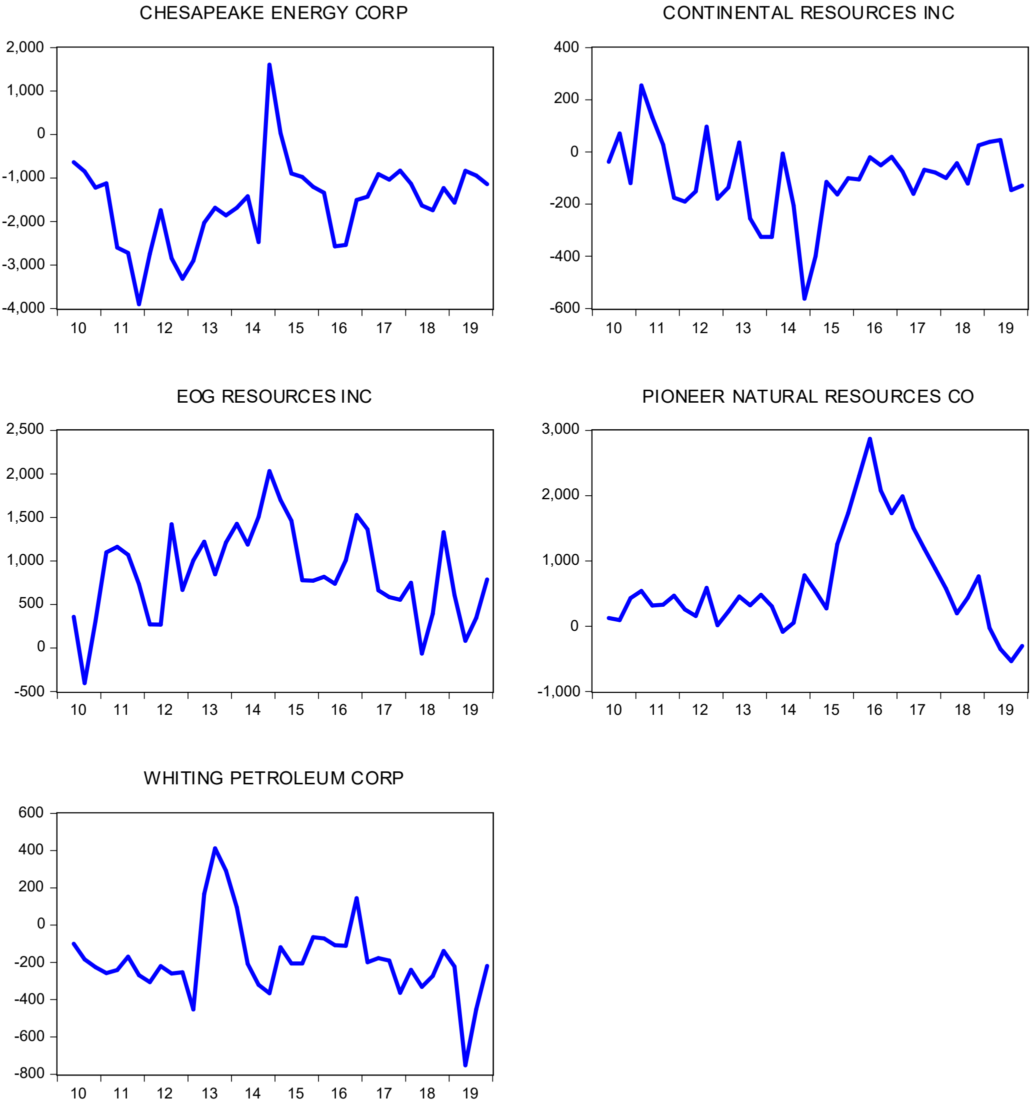


5.5 Some Implications of Fracking Supply Asymmetries

The empirical analysis indicates that the shale-producing regions have an asymmetric supply relation with respect to price changes. The asymmetries of shale oil supply have implications for the comparative statics of oil markets *when they are the marginal or high-cost producers.*[27] The inset to Figure 12 depicts the price movements for supply shifts when the supply curve has a conventional upward slope. In this case, decreases in output by low-cost producers result in a price increase slightly larger than the price decrease resulting from an increase in output by low-cost producers (e.g. OPEC).

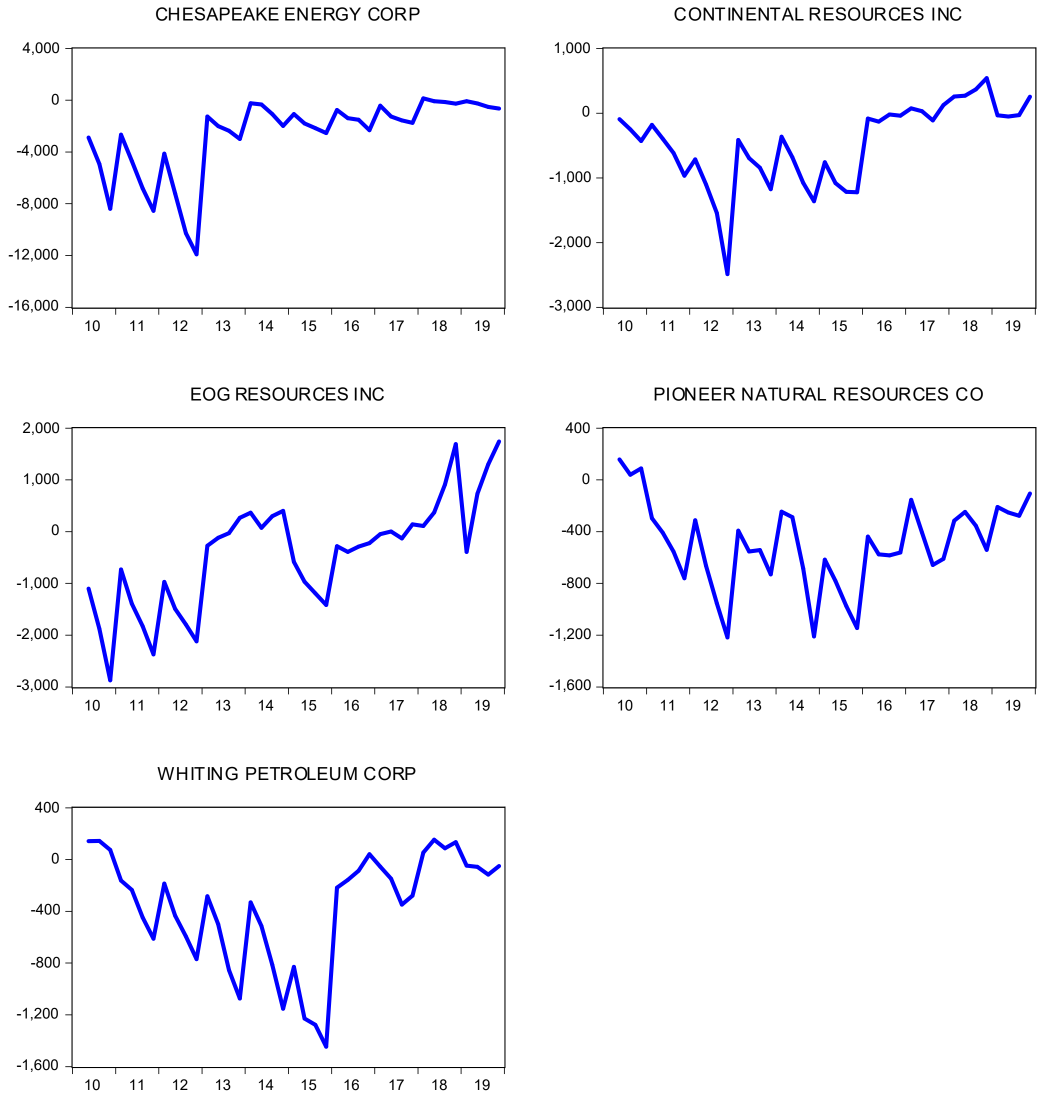
[27] This is similar in spirit to the Brown et al. (2017) analysis of OPEC and the stability of world oil markets. This point has also been made by Dimitropoulos and Yatchew (2018) and Yatchew (2019).

Figure 10: Working Capital of Five Shale Oil Companies (Million USD)



Now consider an asymmetric supply relation that is consistent with the behavior of shale oil producers over the period of analysis. The curve labeled S in the main panel of Figure 12 depicts a supply relation where the elasticity of supply is *larger for price increases than for price decreases* in the neighborhood of the intersection with the demand curve D. What happens when there is an exogenous increase in crude oil output by very low-cost producers (e.g. OPEC)? This would cause the supply curve to shift from S to S^+ in the diagram, resulting in a large fall in prices due to the steepness of the supply curve in this region. What happens when there is an exogenous decrease in oil output by very low-cost producers? This would result in the supply curve shifting from S to S^- in the diagram. In this case the price increase is very small because the supply curve is much flatter in this region. The asymmetric supply response from shale oil producers causes the supply curve to be concave when marginal or incremental production is from the frackers in North Dakota, Texas, and the other oil-shale producing regions.

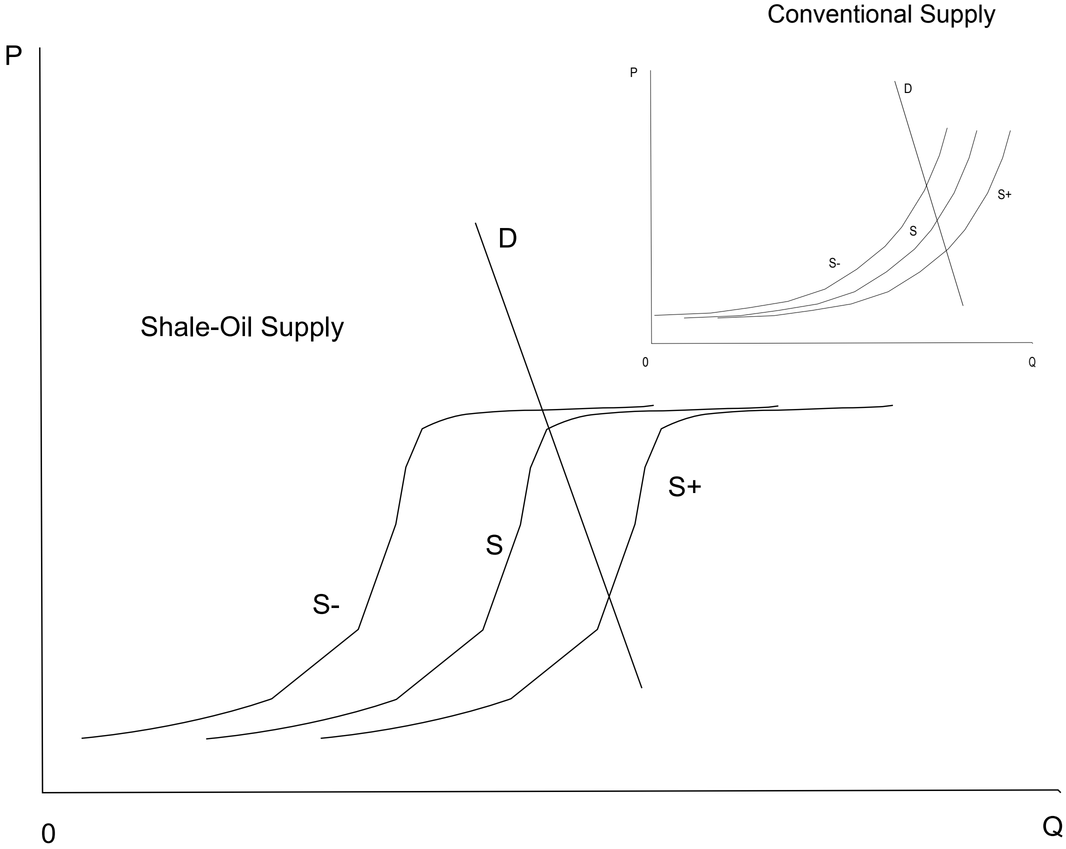
Figure 11: Cash Flow after Capital Expenditure of Five Shale Oil Companies (Million USD)



The asymmetric supply response of shale oil producers within the relevant region of prices—the region in which tight oil production is feasible—has changed the calculus of OPEC oil supply determination. Lowering prices *within this region* did not dramatically decrease shale production. Rising prices *in this region* resulted in a large and rapid expansion in shale oil production. Under the supply conditions that have prevailed, OPEC policies designed to manage the world oil market under conventional supply conditions have proven ineffective.

Future conditions that lessen the asymmetry of high-cost incremental oil supply would be expected to lead to greater OPEC effectiveness at managing world oil markets. In particular, the S-shaped portion of the supply relation is likely to be contingent on continual productivity gains. When productivity gains become exhausted, one would expect a return to a more symmetrical price relationship and a concomitant rise in the effectiveness of OPEC.

Figure 12: Supply Shifts and Price Movements with Asymmetric Supply



5.6 Covid-19 Demand Shocks and Collapsing Oil Prices

The implications of fracker supply asymmetries on the ineffectiveness of OPEC at managing oil markets set out in the previous section are predicated on stable oil demand and tight oil producers accounting for incremental production. When oil demand collapses, as occurred beginning mid-Winter 2020 due to the Covid-19 virus-induced global lockdown, these high-cost producers would be expected to exit the market when oil prices fall below sustainable average variable cost. The supply asymmetries are only relevant when tight oil production through fracking is economically viable. When oil demand eventually returns—and oil prices have already risen substantially from the lows of late April 2020—the assets from bankrupt shale producers, such as Chesapeake Energy and Whiting Petroleum, are likely to once again to be called into production. If and when the tight oil producers with asymmetric supply relations are the incremental producers—the analysis set out in this paper will provide some insight about the comparative statics of oil markets.

6. CONCLUSIONS

The shale oil boom in America—largely the result of the implementation of hydraulic fracturing (fracking) and horizontal drilling technologies—returned the United States to its former prominence as a major producer of crude oil. This paper provides econometric estimates of the supply relation for U.S. oil producers across regions that differ in the use of hydraulic fracturing production methods. The results suggest that fracking has been associated with a structural shift in the oil supply function; non-shale producing regions did not have a structural shift in the oil supply function. In the shale producing regions, the evidence suggests that oil supply responses became asymmetric with respect to price increases and price decreases: The magnitude of the supply response was far larger when prices rose than when prices fell. The magnitude of the supply response with respect to price rises also became much larger since the shale oil boom began in 2008, though the magnitudes have begun to decline in the late shale boom from mid-2011 onward. The changed supply relation for U.S. oil producers over the period of analysis ending in December 2019 is consistent with the ineffectiveness of OPEC policies to increase and stabilize the world price of crude oil.

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REFERENCES

Anderson, S., R. Kellogg, and S. Salant. (2018). “Hotelling Under Pressure.” *Journal of Political Economy* 126(3): 984–1026. https://doi.org/10.1086/697203.

Bai, J. (1997). “Estimating Multiple Breaks One at a Time.” *Econometric Theory* 13: 315–352. https://doi.org/10.1017/S0266466600005831.

Bai, J. and P. Perron (1998). “Estimating and Testing Linear Models with Multiple Structural Changes.” *Econometrica* 66: 72–78. https://doi.org/10.2307/2998540.

Bai, J. and P. Perron (2003a). “Computation and Analysis of Multiple Structural Change Models.” *Journal of Applied Econometrics* 6: 72–78. https://doi.org/10.1111/1368-423X.00102.

Bai, J. and P. Perron (2003b). “Critical Values for Multiple Structural Change Tests.” *Journal of Applied Econometrics* 18: 1–22. https://doi.org/10.1111/1368-423X.00102.

Baumeister, C. and L. Kilian (2012). “Real-Time Forecasts of the Real Price of Oil.” *Journal of Business & Economic Statistics* 30(2): 326–336. https://doi.org/10.1080/07350015.2011.648859.

Baumeister, C. and G. Peersman. (2013). “The Role of Time-varying Price Elasticities in Acounting for Volatility Changes in the Crude Oil Market.” *Journal of Applied Econometrics* 28(3): 1087–1109. https://doi.org/10.1002/jae.2283.

Brown, S. P.A. and H. G. Hillard (2017). “OPEC and World Oil Security.” *Energy Policy* 108: 512–523. https://doi.org/10.1016/j.enpol.2017.06.034.

Brown, J. P., P. Maniloff, and D. Manning (2018). “Effects of State Taxation on Investment: Evidence from the Oil Industry.” *Federal Reserve Bank of Kansas City* RWP 18-07. https://doi.org/10.18651/RWP2018-07.

Collins, G. and Medlock, K. B. (2017) “Assessing Shale Producers” Ability to Scale-up Activity.” *James A. Baker III Institute for Public Policy of Rice University, Houston, Texas*, Issue Brief, No. 01.17.17.

Dahl, C. and T. Duggan (1996). “U.S. Energy Product Supply Elasticities: A Survey and Application to the U.S. Oil Market.” *Resource and Energy Economics* 18: 243–263. https://doi.org/10.1016/S0928-7655(96)00009-7.

Dahl, C. and M. Yücel (1991). “Testing Alternative Hypotheses of Oil Producer Behavior.” *The Energy Journal* 12(4): 117–138. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol12-No4-8.

Dimitropoulos, D. and A. Yatchew (2018). “Discerning Trends in Commodity Prices.” *Macroeconomic Dynamics* 22(3): 683–701. https://doi.org/10.1017/S1365100516000511.

Farzin, Y. (2001). “The Impact of Oil Price on Additions to US Proven Reserves.” *Resource and Energy Economics* 23(3): 271–291. https://doi.org/10.1016/S0928-7655(01)00040-9.

Gately, D. and H. Huntington (2002). “The Asymmetric Effects of Changes in Price and Income on Energy and Oil Demand.” *The Energy Journal* 23: 19–55. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol23-No1-2.

Gately, D. (2004). “OPEC’s Incentives for Faster Output Growth.” *The Energy Journal* 25(2): 75–96. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol25-No2-4.

Gold, R. (2014). *The Boom: How Fracking Ignited the American Energy Revolution and Changed the World*. Simon & Schuster, New York, U.S.A, 1st Edition, ISBN: 978-1-4516-9228-0.

Gold, R. (2014). “Oil Trains Hide in Plain Sight.” *The Wall Street Journal* http://www.wsj.com/articles/oil-trains-hide-in-plain-sight-1417663983, Dec 3, 2014.

Griffin, J. (1985). “OPEC behavior: A Test of Alternative Hypotheses” *American Economic Review* 75(5): 954–963.

Griffin, J. and C. Jones (1986). “Falling Oil Prices: Where is the Floor?” *The Energy Journal* 7(4): 37–50. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol7-No4-2.

Hansen, B.E. (1999). “Threshold Effects in Non-dynamic Panels: Estimation, Testing, and Inference.” *Journal of Econometrics* 93: 345–368. https://doi.org/10.1016/S0304-4076(99)00025-1.

Hansen, B.E. (2000). “Sample Splitting and Threshold Estimation.” *Econometrica* 68(3): 575–603. https://doi.org/10.1111/1468-0262.00124.

Hansen, B.E. (2001). “The New Econometrics of Structural Change: Dating Breaks in U.S. Labor Productivity.” *Journal of Economic Perspectives* 15: 117–128. https://doi.org/10.1257/jep.15.4.117.

Hogan, W. (1989). “World Oil Price Projections: A Sensitivity Analysis.” Prepared pursuant to the Harvard-Japan world oil market study, Energy Environmental Policy Center, John F. Kennedy School of Government, Harvard University, Cambridge, MA, U.S.A.

Jones, C.T. (1990). “OPEC Behaviour under Falling Prices: Implications for Cartel Stability.” *The Energy Journal* 11(3): 117–129. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol11-No3-6.

Kaufmann, R., W. Gruen, and R. Montesi. “Drilling Rates and Expected Oil Prices: The Own Price Elasticity of U.S. Oil Supply.” *Energy Sources* 16(1): 39–58. https://doi.org/10.1080/00908319408909061.

Kilian, L. (2017). “The Impact of the Fracking Boom on Arab Oil Producers.” *The Energy Journal* 38(6): 137–160. https://doi.org/10.5547/01956574.38.6.lkil.

MacAvoy, P. (1982). *Crude Oil Prices as Determined by OPEC and Market Fundamentals*. Ballinger, Cambridge, MA, U.S.A, Second Edition, ISBN 1-59718-073-4.

Newell, R., B.C. Prest, and A. Vissing (2016). “Trophy Hunting vs. Manufacturing Energy: The Price Responsiveness of Shale Gas.” Resource for Future Discussion Paper, August, 16–32. https://doi.org/10.3386/w22532.

Newell, R. and B.C. Prest (2018). “The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata.” NBER Working Paper, No.23973, Ocotber, 2018. https://doi.org/10.3386/w23973.

Newell, R. and B.C. Prest (2019). “The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata.” *The Energy Journal* 40(3): 1–30. https://doi.org/10.5547/01956574.40.3.rnew.

Newell, R., B.C. Prest, and A. Vissing (2019). “Trophy Hunting versus Manufacturing Energy: The Price Responsiveness of Shale Gas.” *Journal of the Association of Environmental and Resource Economists* 6(2): 391–431. https://doi.org/10.1086/701531.

Perron, P. (2006). “Dealing with Structural Breaks.” *in Palgrave Handbook of Econometrics* 1: 1–22.

Rao, N. (2018). “Taxes and US Oil Production: Evidence from California and the Windfall Profit Tax.” *American Economic Journal: Economic Policy* 10(4): 268–301. https://doi.org/10.1257/pol.20140483.

Yatchew, A. (2019). “How Scalability is Transforming Energy Industries.” *Energy Regulation Quarterly* 7(2).