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Impacts of COVID-19 on Tight Oil Supply

Evidence from a Price Responsiveness Econometric Model

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Yan Chen*

Abstract

The coronavirus pandemic is having substantial impacts on the oil and gas industry. Following the plummeting of oil prices in March 2020, the future supply of tight oil in the United States has become crucial for government policy. Market prediction, however, is not well established. In this paper, I construct an econometric model to quantify the price responsiveness of tight oil supply in the United States using well-level play-specific panel data, and use the model to analyze the influence of coronavirus pandemic on tight oil supply. The regression results show that the oil price elasticity was 2.0 for tight oil drilling and 0.5 for tight oil production in 2010-2016. The gas price elasticity is insignificant in both cases. Forecasts using the estimated econometric model show that tight oil production will decrease by 1.3-2.3 MMbbl/d (16-28%) under different price scenarios. The coronavirus pandemic will also cause a significant reduction in tight oil drilling activities. However, tight oil is not likely to be a "swing producer" and OPEC will continue to lead production cuts under low prices.

Keywords: tight oil; elasticity; oil price; Coronavirus; OPEC; swing producer

JEL Codes: Q32, Q41, D24

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1. Introduction

Coronavirus disease (COVID-19) has caused a worldwide economic recession that is much more severe than the 2008 financial crisis [1]. Its influence on the oil industry is especially large because quarantines and lockdowns sharply reduce the demand for oil and lead to a collapse of oil prices. The low oil prices will further influence upstream development and oil supply. Oil from shale and tight sand plays (tight oil) covers more than 60% of the crude oil production in the United States in 2020 [2]. Therefore, evaluating the influence of oil prices on tight oil supply is important to forecast crude oil supply in the United States.

Although tight oil production started as early as the 1950s [3], its development was limited in the 20th century due to the very low reservoir permeability and low productivity. The integration of hydraulic fracking and horizontal drilling technology has greatly increased the per-well productivity as well as the total extraction from tight oil plays. The total tight oil production increased substantially from 2010 and reached its first peak in 2015 (Fig.1). The rapid increase of tight oil triggered the collapse of global oil prices in mid-2014, which was intensified by OPEC’s decision in November 2014 not to reduce production [4]. The oil price fell from above 100 USD/bbl in mid-2014 (Western Texas Intermediate-WTI spot price, USD/bbl: US dollars per barrel) to about 30 USD/bbl in early 2016 (Fig.1). The one and half years’ price drop led to the first and only long-term production decline in tight oil’s history. Oil prices declined from 63 USD/bbl in early January 2020 to 45 USD/bbl by the end of February 2020, [5] corresponding to the pandemic-induced demand cut of crude oil. They were driven even lower by the price war between Russia and OPEC in the short run [6], but will depend on the demand-supply balance in the long run. The coronavirus pandemic is estimated to last 1-2 years [7], which suggests a low oil price period comparable to the 2014-2016 price collapse. Therefore, the responsiveness of tight oil activities in 2014-2016 provides an analogy to estimate possible influences of the COVID-19 pandemic on the tight oil industry.

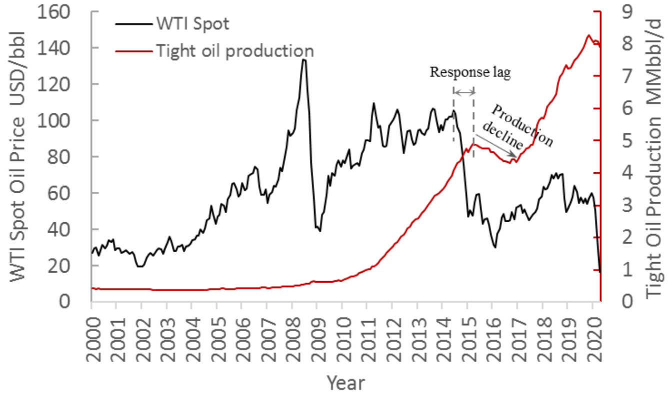

Figure 1. WTI spot oil prices [5] and total tight oil production [8] in 2000-2020 in the United States.

The influence of energy prices on tight oil supply has been evaluated by several studies and the research topics cover tight oil reserves, production, and the number of wells drilled. The research methods include econometric analysis [9–11], discounted cash flow [12], and qualitative discussion [13]. Smith and Lee [12] examined the price responsiveness of tight oil reserves using the discounted cash flow method. The authors reported back-calculated oil price elasticities of 0.3~0.5 for tight oil reserves and 0.6~1.0 for economically viable drilling sites. Bjørnland et al. [10] found that both well completion and tight oil production in North Dakota responded significantly to the spread between spot and future oil prices. Umekwe and Baek [9] discovered that tight oil production responded asymmetrically to oil prices, with a short-run price elasticity of -0.056 during a price decline and 0.079 for a price increase. Newell and Prest [11] estimated an oil price elasticity of 1.6 for the number of tight oil wells drilled. In addition to the above quantitative analysis, Kleinberg et al. [13] discussed the tight oil market dynamics qualitatively and attributed the reason for low responses of tight oil production in 2014-2016 to different half-cycle breakeven costs.

The above studies provide the first batch of information on the influence of oil prices on tight oil supply. However, the estimated results fall in a wide range and no two of them are close. This makes it difficult to select a reliable value to estimate the influence of the COVID-19 pandemic. A detailed examination of the three econometric analyses [9–11] shows that they are all based on aggregate time series data and do not consider the differences among tight oil plays. Besides, most studies use data from a few tight oil plays which cover a limited fraction of the entire tight oil reservoirs. Given the limited knowledge about tight oil development under a price collapse, and the importance of it to predict crude oil supply, it is necessary to conduct more research in this area. The purpose of this study is to 1) construct an econometric model to quantify the price responsiveness of tight oil supply in the United States using well-level play-specific panel data that cover all major tight oil plays and include the 2014-2016 price decline period, and 2) use the model to analyze the influence of coronavirus disease on tight oil supply. The study estimates the oil and gas price elasticities for both tight oil drilling activity and tight oil production. The high-resolution data allows econometric modeling based on a fixed effect approach that is possible to control unobserved heterogeneity across the plays and obtain more accurate estimates.

2. Models and Methods

Econometric models have been widely used to estimate the influence of energy prices on crude oil supply [14–16]. In this study, a fixed effect econometric model is used to quantitatively estimate the influence of energy prices on tight oil drilling activity and production. Drilling activities are measured using the number of new wells drilled in a quarter. Production is measured by the average daily tight oil production. Because companies have to file for permits, contract with suppliers, build well pads and do other things necessary to start drilling a well, I use quarterly data to cover the period between making a drilling decision and starting to drill a well. The selection of quarterly data is also supported by Bjørnland et al. [10], which found that the number of monthly completed new wells did not respond to spot oil prices.

Independent variables include lagged spot oil and gas prices and control variables. Spot prices are substitutes for the expected long-term energy prices when companies make drilling decisions. Since we cannot observe the actual decision process, researchers use different methods to calculate price substitutes. Common methods include the random walk price model [17], the average of past prices [18], spot prices [14], and future prices [19]. Studies show that these methods have similar predictive power for future energy prices [20]. Given the data availability for each tight oil play, I choose spot prices to represent the expected oil and gas price.

Three lags of oil and gas prices, i.e., t-1, t-2, and t-3, are included to cover the decision process of most oil and gas companies. Companies of different sizes have different development plans. Some huge international oil companies make annual or semi-annual working plans, while small independent companies may respond more promptly to market signals. The lag of three quarters should be able to account for the drilling plan adjustment of most companies. I use the upstream cost index and the housing price index to control for the influence of development cost and economic crisis.

Oil and gas prices are reported to be non-stationary in levels but stationary in first difference [21,22]. Therefore, I transfer the level data into percentage-change values (Equation 1) before conducting regression analysis. After transformation, the dependent and independent variables are dimensionless and the estimated coefficients are price elasticity. The transferred data is tested for stationarity using a panel unit root test allowing cross-section dependence [23].

The data transformation formula (Equation 1) and the econometric model fixing the effect of individual tight oil play (Equation 2) are as follows.

$$y_{it} = \frac{z_{it} - z_{i,t-1}}{z_{i,t-1}} \quad (1)$$

where y_{it} is the percentage change of z_{it}; and z_{it} is the level value of a variable.

$$y_{it} = \beta_i + \sum_{m=1}^{3}\left[\beta_{1,m} p_{i,t-m}^{g} + \beta_{2,m} p_{i,t-m}^{o}\right] + \gamma' X_{i,t-1} + \varepsilon_{it} \quad (2)$$

with y_{it} representing the percentage change of the number of new wells drilled in reservoir *i* from time *t-1* to t, or the percentage change of tight oil production of reservoir *i* from time *t-1* to *t*; $p_{i,t-m}^{o}$ representing the percent change of crude oil prices in reservoir *i* from time *t-m-1* to time *t-m*; $p_{i,t-m}^{g}$ representing the percent change of gas prices in reservoir *i* from time *t-m-1* to time *t-m*; $X_{i,t-1}$ representing the percent change of control variables in reservoir *i* from time *t-2* to time *t-1*, such as the upstream cost index, and the housing price index; and $\varepsilon_{i,t}$ representing the random error.

I design different scenarios to evaluate the variation in price elasticities. The base case includes data from 2010 to 2016, which covers the 2014 price collapse. Chen and Xu [22] reported that oil and gas prices did not influence shale gas development in 2000-2008 because of low well productivity. The average productivity of tight oil wells was low before 2009, but the drilling history is different from that of shale gas. To test the difference between shale gas and tight oil development, a scenario including data from 2000 to 2008 is analyzed. I also design scenarios to test the influence of structural breaks in oil and gas prices [24], and to test the robustness and sensitivity of model settings and selection of energy prices. The details of scenario design are described in Section 4.

When the parameters are estimated, the base-case econometric model is used to forecast tight oil production under different price scenarios.

3. Data

3.1 Drilling Data

Well-level drilling data provided by Drillinginfo (a company collecting and distributing oil and gas upstream data [25]) is used to analyze the drilling behavior of major tight oil plays in the United States. The full database contains over 3.6 million wells drilled since the 1910s. The database does not label reservoir categories (e.g., tight oil, shale gas, or conventional oil and gas) or lithology (e.g., shale, sandstone, limestone, etc.) of the completed formation (the rock unit that produces hydrocarbon). Therefore, it is impossible to identify tight oil wells directly from the database. To overcome this problem, I compiled a list of tight oil reservoirs based on the publication of EIA and other institutes [26–28], and then manually downloaded well data for the listed reservoirs with the production type selected as either “oil” or “oil and gas”. An “approximate string match” technique is used to ensure that all wells from the same reservoir are included [22]. I also analyzed the regional geology, hydrocarbon maturity, gas-to-oil ratio (GOR) and lithology of each play to allocate the “oil and gas” wells into either oil or gas type, and keep oil wells for this study. Oil and gas are joint products of most hydrocarbon reservoirs. The term “oil and gas” is a field terminology that needs to be specified. Wells labeled as “oil and gas” appear in Bakken, Marcellus, Utica, and Point Pleasant formations. They are classified as oil wells in the Bakken formation and gas wells in Marcellus, Utica, and Point Pleasant.

According to SPE et al. [29], tight oil is defined by the rock containing it rather than the well types used to develop it (e.g., horizontal and vertical). Therefore, I include all well types as long as they are producing from a tight play. This is different from the methodology used in other literature [10,11], which equates horizontal wells to unconventional and vertical wells to conventional. I exclude wells with a spud date later than the first production date, and wells missing spud and first production date, because it is difficult to identify their true drilling time. Formations with limited oil production, such as Marcellus and Haynesville, are not included either. The final dataset contains 44,967 wells in nine tight oil plays from seven states drilled between January 2000 and June 2016 (Fig. 2).

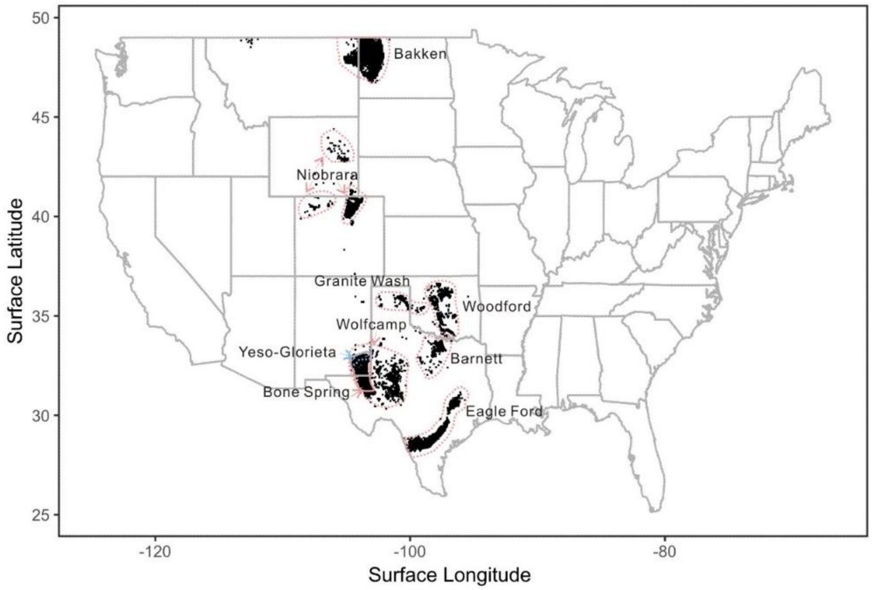

Figure 2: The location of tight oil wells drilled in 2000Q1-2016Q2. The outline of tight oil plays (pink lines) is from EIA [30]. Surface coordinates of tight oil wells (black dots) are from Drillinginfo [25].

Table 1 presents the summary statistics of the key characteristics of tight oil plays in the period 2000-2016. The well number in Column 1 shows the total number of tight oil wells drilled in each play (after data screening). Bakken and Eagle Ford are the most extensively drilled plays, with over 12,000 wells. Barnett, which is extensively drilled for shale gas, has only 583 oil wells. The average peak oil production in Column 2 (IPOD, initial production of oil per day) reflects the productivity of different reservoirs. The initial productivity of Bakken and Eagle Ford is in the range of 400-500 barrels per day (bbl/d). They are the first tier of the nine plays. The second tier includes Bone Spring, Wolfcamp, and Granite Wash, whose peak oil production is in the range of 200-400 bbl/d. The third tier includes Barnett, Niobrara, Woodford, and Yeso-Glorieta, whose peak oil production is less than 200 bbl/d. Column 3 shows the average productivity of associated natural gas (IPGD, initial production of gas per day) and Column 5 the average gas to oil ratio (GOR). The key characteristics show that tight oil plays are heterogeneous in both geology and drilling intensity. Therefore, models using aggregated data may overlook these individual characteristics.

Table 1. Summary Statistics of all Tight Oil Plays

Column	(1)	(2)	(3)	(4)	(5)	(6)
Reservoir	Well Number 2000-2016	IPOD bbl/d	IPGD 10^3 m^3/d	MD m	GOR m^3/bbl	Perforation m
Bakken	12519	461	13	5925	34	2732
Barnett	583	76	7	2797	259	574
Bone Spring	2925	387	22	4061	125	1219
Eagle Ford	12044	491	18	4814	47	1656
Granite Wash	352	225	21	3892	342	725
Niobrara	10632	122	8	2840	124	470
Wolfcamp	2392	308	18	3966	174	1119
Woodford	1133	187	20	4243	2894	1489
Yeso-Glorieta	2387	77	3	1553	72	365
Total	44967	342	14	4342	146	1533

Notes*:* Well number: the number of wells drilled between January 2000 and June 2016; IPOD: peak daily crude oil production; IPGD: peak daily gas production; MD: measured depth; GOR: gas-to-oil ratio; Perforation: the length of wellbore perforated. bbl/d: barrels per day; 10^3 m^3/d: thousand cubic meter per day; m: meter; m^3/bbl: cubic meters per barrel.
Source: Calculations based on well-level data from Drillinginfo [25].

Figure 3 shows the trends of major characteristics of tight oil and oil and gas prices in 2000-2016. The total number of new tight oil wells drilled in each quarter increased from 80 in 2000Q1 to 2,200 in 2014Q2 (Fig 3a). However, it plunged quickly from a peak in 2014Q2 to less than 500 per quarter in 2016. Facet plots of individual plays show that Bakken and Eagle Ford contribute to most of the new wells drilled after 2009 and tight oil plays vary in the start date and intensity of development (Fig. 4).

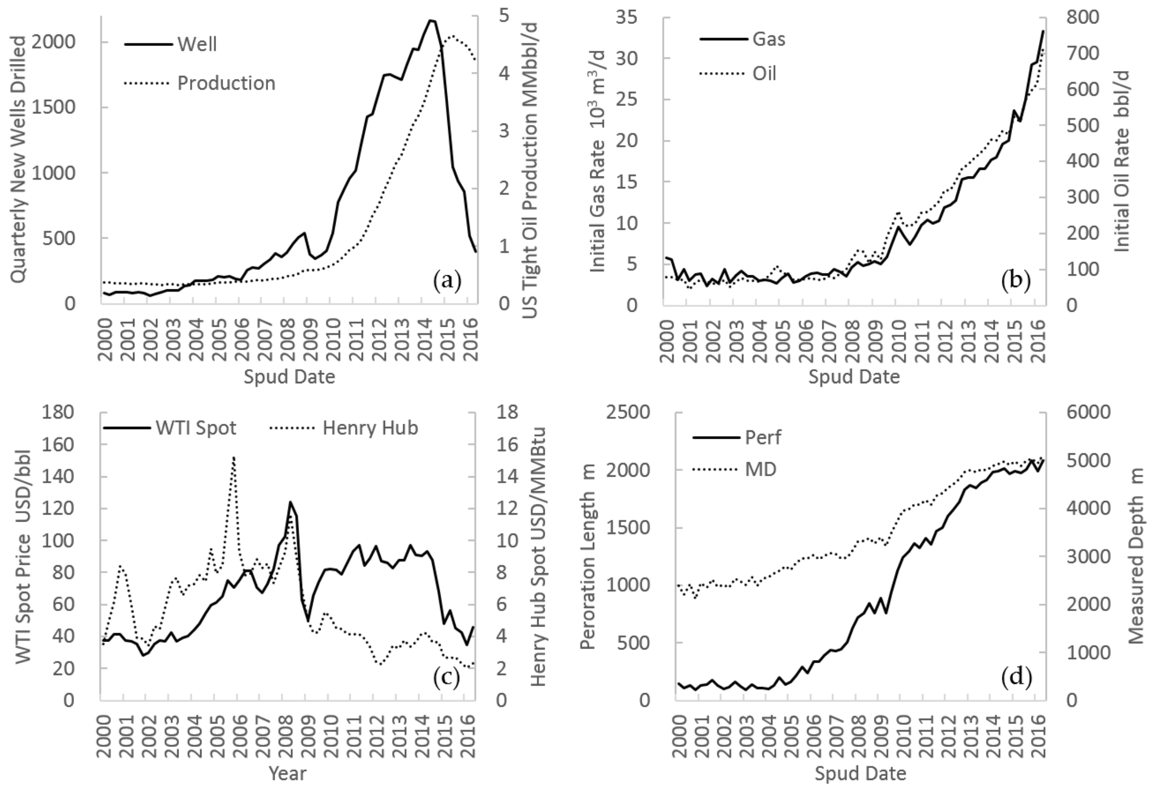

Figure 3: (a) Quarterly profile of new wells drilled and total tight oil production in the United States; **(b)** the average initial oil and associated natural gas production; **(c)** WTI spot price for crude oil and Henry Hub spot price for natural gas; and **(d)** the average perforated interval and measured depth.

The oil and gas productivity of new wells shows a different pattern. They were low before 2009 and increased continuously afterward without decline (Fig. 3b). The average initial oil productivity increased from 100 bbl/d in 2008 to 700 bbl/d in 2016. The average initial gas productivity increased from 5,000 m^3/d (cubic meters per day) in 2008 to 30,000 m^3/d in 2016. Oil and gas productivities increased 5-6 times and the gas-to-oil ratio (GOR) remained almost constant. The average initial tight oil productivity plot of each play indicates that both the shape and absolute value of productivities vary substantially among tight oil plays (Fig. 5). The timing of the productivity increase reflects the expansion pace of the new technology in each play.

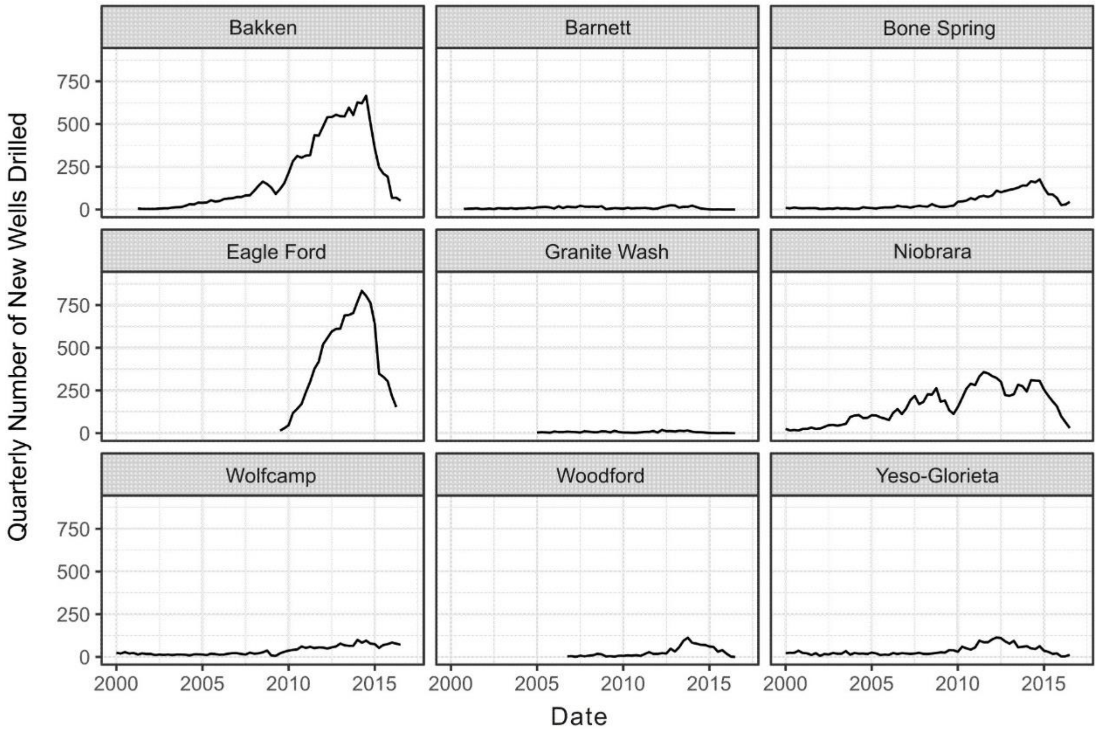

Figure 4: The quarterly number of new wells drilled in each tight oil formation

Fig. 3d shows the average length of the perforated interval and measured depth (MD). The length of the perforated interval started to increase from about 150 meters in 2005 to more than 2000 meters in 2016. Theoretically, the length of perforation should be proportional to well productivity, ceteris paribus. But other factors, i.e., reservoir productivity, fracking technology, and geological heterogeneity all influence well productivity. The integration of horizontal drilling and slickwater fracking was the prelude to the shale revolution around 2002, when Michell Energy and Devon Energy merged [31]. This technology was quickly applied to tight oil development in the Bakken formation in 2003 [32]. However, it appears that what succeeded in shale gas development did not work well for tight oil. The acceleration of tight oil development began in 2009 when the Continental Resources company discovered the repeated fracking method to produce a significant amount of oil from Bakken [32]. The EOG company also discovered the high-productivity Eagle Ford play in 2009 [32]. Plots in Figure 3 (a, b and d) are consistent with the technology advancement history.

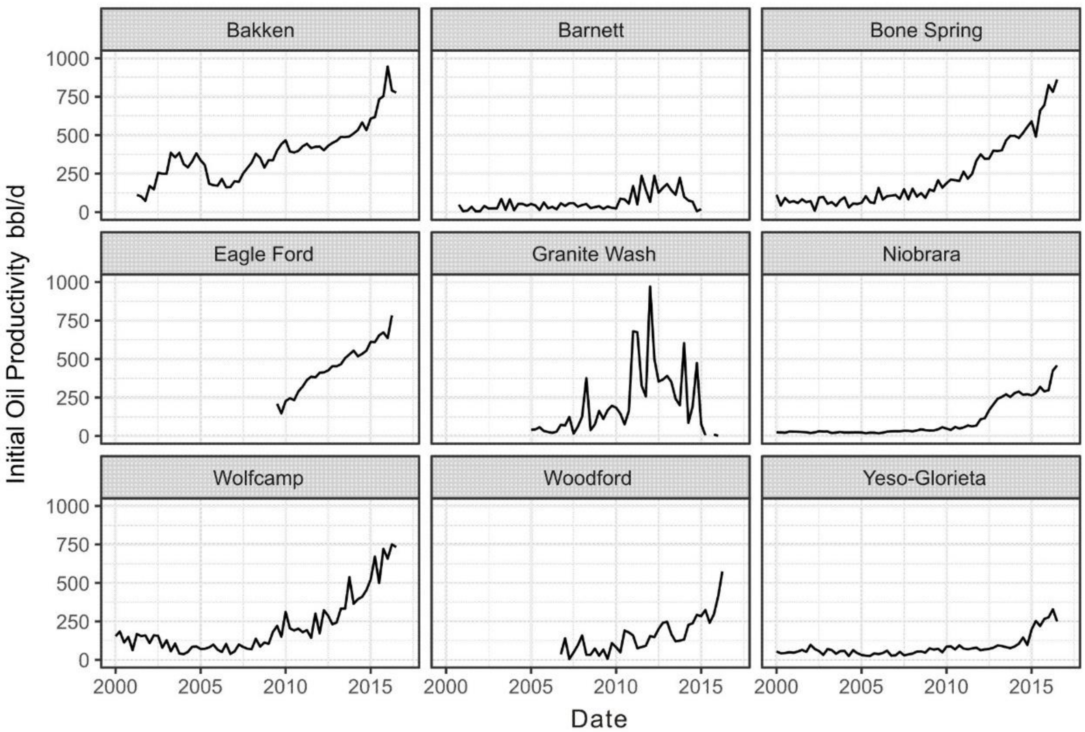

Figure 5: The average initial oil productivity of new wells in each formation

3.2 Oil and Gas Price Data

The West Texas Intermediate (WTI) oil price is widely used as a benchmark for world crude oil prices. However, the wellhead prices for different fields may be different from the WTI price. Therefore, I used synthetic oil prices for each tight oil play to estimate price elasticities. The synthetic oil prices were computed using EIA's first purchase price of crude oil in each state [33], and oil prices from Enterprise Products Partners L.P [34] (a company with business in oil and gas pipelines, natural gas processing, and natural gas liquid (NGL) importing/exporting in the United States). The WTI oil price is used to forecast total tight oil production. Detailed calculation methods are provided in the supplementary material (Table A1). The nominal monthly crude oil prices are converted to real prices in U.S. dollars (USD) as of January 2016 using the producer price index (PPI) data from the U.S. Bureau of Labor Statistics (BLS) [35]. The real monthly data is further upgraded to quarterly prices.

Figure 6a plots the quarterly oil prices for nine tight oil plays. Oil price had a large variation in the period 2000-2016, with the highest value of 124 USD/bbl and the lowest value of 24 USD/bbl (2016 price level). The price was on a general upward trend from 2000 to 2008, with an average of 58.5 USD/bbl. It declined to 50 USD/bbl during the 2008 financial crisis, but rebounded quickly and maintained about 90 USD/bbl in 2010-2014. Oil prices plunged again at the end of 2014 and decreased to 35 USD/bbl in 2016. However, the average WTI oil price in 2009-2016 was 75 USD/bbl, higher than the average price in 2000-2008. The WTI oil price increased above 60 USD/bbl in 2018 (Fig.11b) and the average was 53 USD/bbl in 2017-2019. Despite the overall similar trends, prices in different plays showed substantial variation. The difference was as high as 20 USD/bbl at some times.

The shale gas price indexes (SPI) of different basins from Natural Gas Intelligence (NGI, a company providing natural gas price data) provide a good estimate for the delivered-to-pipeline associated natural gas prices of each tight oil play. Because SPI is only available from 2010 onward, I compute synthetic gas prices using selected conventional gas price points that are used for shale gas price index estimation by NGI [28]. Supplementary Table A2 shows the detailed computation scheme. Daily SPI values were averaged to obtain monthly gas prices and then converted to real prices as of January 2016 US dollars using the PPI data from BLS [35]. Real monthly data were further averaged to obtain quarterly prices. The synthetic prices matched well with the NGI reported SPI, as shown in the Niobrara and Eagle Ford cases (Fig. 7). Fig 6b plots the quarterly gas prices for the nine tight oil plays. Gas prices showed two stages separated by the 2008 financial crisis. In 2000-2008, the gas price was, in general, high and volatile. The average Henry Hub spot price was 7.7 US dollars per million British thermal units (USD/MMBtu) in 2000-2008. The difference between the lowest and highest gas price was over 10 USD/MMBtu (Fig. 3c). From 2009 to 2016, the gas price was less volatile and remained at a low level. The difference between the lowest and highest gas price was 3.5 USD/MMBtu and the average Henry Hub spot price was 3.6 USD/MMBtu in 2009-2016 (Fig. 3c). Again, despite the similar price trends, gas prices showed substantial variation among the plays at some times. The difference was as high as 5 USD/MMBtu around 2007 (Fig. 6b).

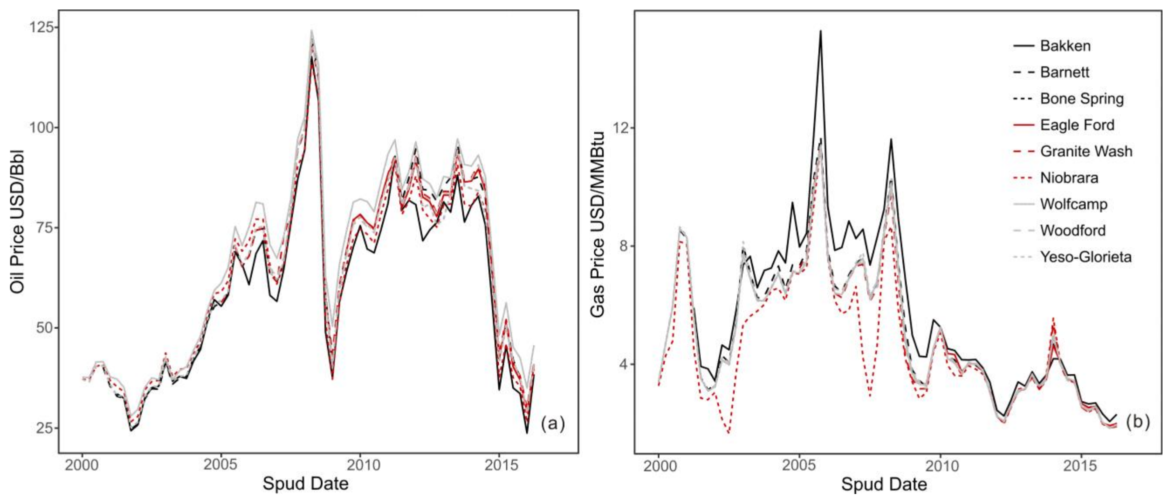

Figure 6: (a) Quarterly profiles of the crude oil prices, and **(b)** natural gas prices for each tight oil play. Legend is the same for both plots.

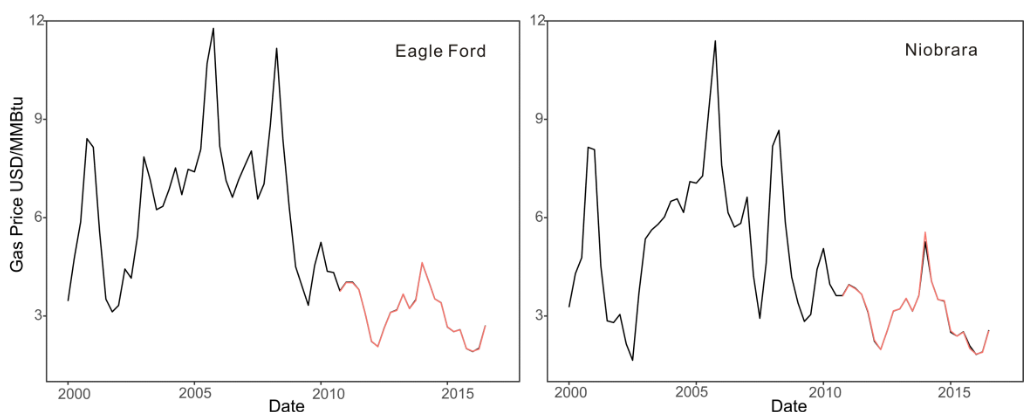

Figure 7: Synthetic natural gas prices (black) and NGI-reported SPI (red) for selected tight oil plays.

3.3 Production Data

The play-level production data [8] from the nine tight oil plays in Table 1 are used to estimate the parameters in the econometric model. The total tight oil production data in the United States [8] are used to forecast tight oil production. The original monthly production data is averaged to obtain quarterly production data. The data is different from the well-level initial productivity described in Section 3.1. Instead, it includes oil production from both legacy wells and new wells. The total tight oil production in the United States was less than 0.5 million barrels per day (MMbbl/d) before 2008 (Fig 3a). It increased rapidly starting in 2009 and reached the first peak of 4.9 MMbbl/d in

2015Q2, then declined to 4.3 MMbbl/d during the 2014 price collapse [8]. The production climbed up again from 2017 and reached 8.2 MMbbl/d at the end of 2019 (Fig. 11a). Examination of the play-level data shows that the production from individual plays was highly heterogeneous (Fig. 8). High-production plays such as Bakken and Eagle Ford produced more than one million barrels per day in 2015 and have contributed to more than 50% of the total tight oil production since 2012 [8]. Wolfcamp, Niobrara, and Bone Spring were in the second tier, which produced 0.3-0.4 MMbbl/d at peak level. Production from Granite Wash, Woodford, and Yeso-Glorieta was less than 0.1 MMbbl/d. Plots in Fig. 8 indicate that the decline in total production since mid-2015 came mainly from Bakken and Eagle Ford. Other plays show little decline and some even increased.

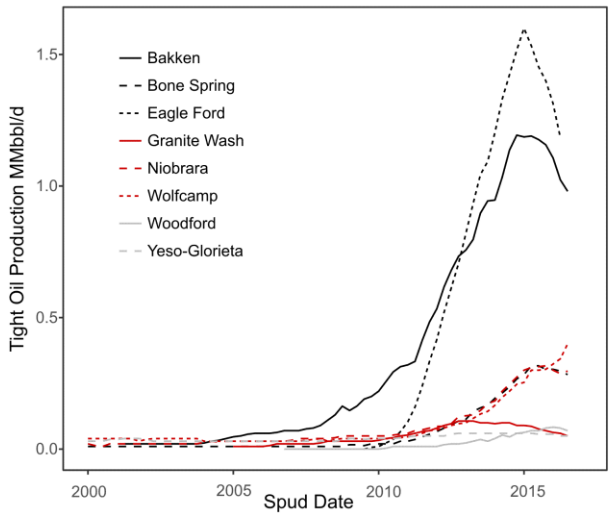

Fig. 8. The production of individual tight oil plays in 2000-2016. Data source: EIA [8].

3.4 Other Data

Cost is an important factor for drilling decisions. I use the upstream cost index data estimated by iHS (a company providing intelligence services for the petroleum industry) as a substitute for the real development cost. The data is a quarterly cost index evaluating the trends of drilling, completion, facilities, and operation cost of different shale and tight plays. The original nominal index is transferred to real terms with 2016Q1 as the base using the quarterly PPI data published by the Organisation for Economic Co-operation and Development (OECD) [36]. The real upstream cost of tight oil was generally increasing before 2008, when the demand for drilling and completion services exceeded supply due to the shale gas boom (Fig. 9a). After a rapid decline during the financial crisis, the cost of most plays recovered to a high level and remained stable until the new plunge in 2015. However, Barnet and Granite Wash show a continuous declining trend (Fig. 9a). The plots also show that the heterogeneity among plays increased after 2009 (Fig. 9a).

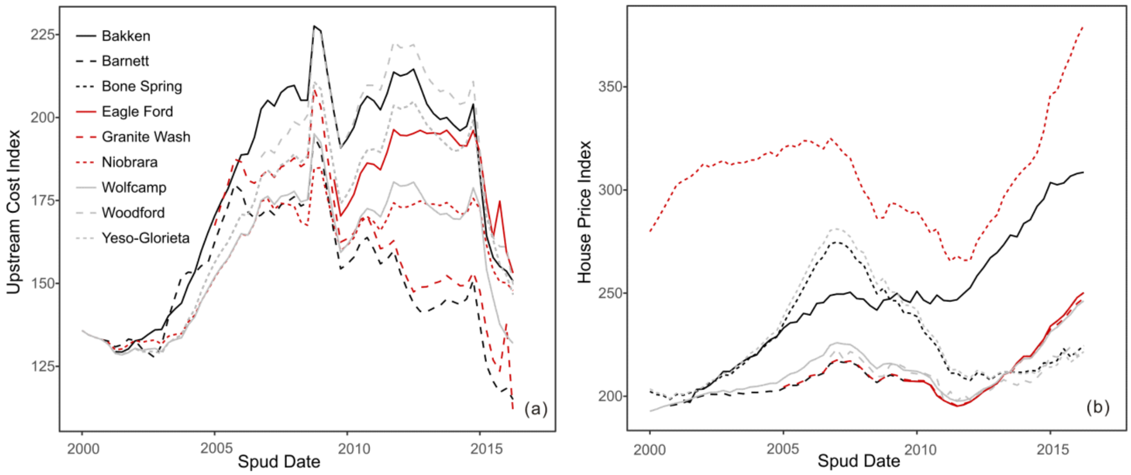

Figure 9: (a) Quarterly profiles of the upstream cost indexes for tight oil plays, and **(b)** associated house price indexes. Legend is the same in both plots.

The 2008 financial crisis had a large effect on energy prices and tight oil drilling activities, as shown in Fig. 3. I use the seasonally adjusted nominal house price index (HPI) [37] to control for the effect of the financial crisis. The index tracks the movement of single-family house prices since 1991. The original nominal data was converted to a real price index as of 2016Q1 using the Consumer Price Index (CPI) from the Federal Reserve Bank [38]. Since the HPI is reported by states, I calculate a weighted average HPI for each tight oil play using the number of wells drilled in each state as weights (Table A3). The house prices increased from 2000 to 2007 and started to decline in early 2008 (Fig. 9b). They reached a local trough around 2011 and then increased all the way up until the end of my sampling period. The house prices associated with different plays, as well as the relative changes, showed substantial heterogeneity (Fig. 9b).

4. Results

4.1 Price Elasticities of Tight Oil Supply

Unit root tests using the CIPS method for panel data [23] show that the percentage-change values of the well number, gas price, and oil price are all stationary

(Table 2). Therefore, the proposed fixed effect model can be applied to the transformed data.

Table 2. Unit Root Test Results for the Transferred Variables

	Lag 2	Lag 3	Lag 4
Well	6.9***	5.8***	5.2***
Gas Price	6.2***	3.7***	3.5***
Oil Price	6.7***	5.6***	5.2***

Notes: The lag number is the order used for Dickey-Fuller augmentation.
*** Significant at the 1 percent level. ** Significant at the 5 percent level.

Table 3 shows the regression results for tight oil drilling and production. Cases 1-3 estimate the responses of tight oil drilling activities and cases 4-6 estimate the responses of tight oil production to oil and gas prices. Cases 1 and 4 are the base scenarios, which include data from 2010 to the second quarter of 2016 (2010Q1-2016Q2). The results show that gas price has an insignificant effect on tight oil drilling and production, whereas oil price has a significant effect. Oil price elasticity is 2.03 in case 1, about four times the elasticity of tight oil production (0.53, case 4). Cases 2 and 5 include data from 2000 to 2008Q3 and the results show that neither energy price is significant in this period. Cases 3 and 6 regress on data from 2000 to 2016Q2. The oil price elasticity is 0.84 for tight oil drilling and 0.21 for tight oil production, both of which are about 40% of the results in 2010-2016.

Table 3. Regression Results for Tight Oil Drilling and Production

Dependents	Number of Wells			Production		
	Case 1	Case2	Case 3	Case 4	Case 5	Case 6
	2010-2016	2000-2008	2000-2016	2010-2016	2000-2008	2000-2016
lag(GasPrice, 1)	-0.09	-0.28	-0.2	0.04	-0.02	-0.01
	(0.19)	(0.19)	(0.13)	(0.06)	(0.03)	(0.03)
lag(GasPrice, 2)	-0.3	0.3	0.13	-0.1	-0.02	-0.06**
	(0.18)	(0.18)	(0.12)	(0.05)	(0.03)	(0.03)
lag(GasPrice, 3)	-0.12	-0.09	-0.12	0.01	0.01	0.02
	(0.19)	(0.19)	(0.12)	(0.05)	(0.03)	(0.03)
lag(OilPrice, 1)	1.03***	0.3	0.69***	0.12	0.07	0.03
	(0.26)	(0.39)	(0.18)	(0.08)	(0.07)	(0.04)
lag(OilPrice, 2)	1.03***	0.58	0.33	0.21***	0.02	0.10**
	(0.27)	(0.39)	(0.17)	(0.08)	(0.07)	(0.04)
lag(OilPrice, 3)	-0.04	-0.17	-0.18	0.20**	0.07	0.07
	(0.28)	(0.39)	(0.19)	(0.08)	(0.07)	(0.05)
lag(Cost, 1)	0.03	-1.67	0.48	0.26	-0.54	0.39
	(1.10)	(2.63)	(0.83)	(0.33)	(0.55)	(0.20)
lag(House, 1)	-0.38	5.28	-0.02	-1.16	-0.16	-1.09***
	(2.23)	(4.12)	(1.83)	(0.65)	(0.73)	(0.42)
Sum.GasPrice	-0.5	-0.08	-0.2	-0.05	-0.03	-0.05
	(0.32)	(0.33)	(0.22)	(0.09)	(0.06)	(0.05)
Sum.OilPrice	2.03***	0.7	0.84***	0.53***	0.16	0.21***
	(0.47)	(0.68)	(0.31)	(0.14)	(0.12)	(0.07)
F	4.39	1.17	4	8.5	2.5	12.48
p-value	0	0.32	0	0	0.01	0
R-Squared	0.17	0.06	0.08	0.31	0.13	0.23
N	205	189	450	182	161	391

Notes: Sum.GasPrice and Sum.OilPrice are the computed long-term elasticity; Standard errors in parentheses. 2010-2016: 2010Q1-2016Q2; 2000-2008: 2000Q1-2008Q3; 2000-2016: 2000Q1-2016Q2. Q1: the first quarter of a year.
*** Significant at the 1 percent level. ** Significant at the 5 percent level.

The above analysis indicates that tight oil supply responded differently in the two periods separated by 2009, and commingling data from the entire period yields oil price elasticities in between the two end values. The time around 2009 is a special period when the financial crisis and the shale gas boom occurred together. A change in the relationship between oil and gas prices is also observed [22,24].

In order to analyze the evolution of oil price elasticity and select the correct data breakpoint, I run regressions on data with a successive change in endpoints. For the period before 2009 (period I), all data groups start in 2000Q1, and end between 2007Q1 and 2009Q2 (i.e., 2000Q1-2007Q1, 2000Q1-2007Q2, ……, 2000Q1-2009Q2); for the period after 2009 (period II), all data groups end in 2016Q2, but start between 2008Q1 and 2010Q2 (i.e., 2008Q1-2016Q2, 2008Q2-2016Q2, ……, 2010Q2-2016Q2). Figure 10 plots the mean and 95% confidence interval of oil price elasticities of tight oil drilling in the two groups. The elasticities in period I are insignificant in all regressions, although most of the mean values are in the range of 0.7-1.0. The elasticities are significant in all regressions in period II and decrease gradually from 2 to 1 when the starting point extends from 2009Q2 to 2008Q1 (Fig. 10). From 20008Q1 to 2009Q1, oil price elasticities of the two groups are indistinguishable from each other. The analysis shows that the responsiveness of tight oil drilling to oil price changes from insignificant in period I to 2 in period II and the transitional period is 2008Q4-2009Q1.

Table 4 summarizes the estimated price elasticity of tight oil supply from Newell and Prest [11], Smith and Lee [12], Bjørnland et al. [10], and this study. The study of Newell and Prest [11] is the most similar to this research; it reported an oil price elasticity of 1.63 in 2005-2015. Because their data covered the transition period in 2009, the lower value of 1.63 is consistent with the price elasticity variation analysis. The production responsiveness of 0.53 is close to the simulated one-year production response in Newell and Prest [11] and the 0.3-0.5 reserve responsiveness in Smith and Lee [12]. The production responsiveness in Bjørnland et al. [10] is much lower than the estimation of other studies because they conducted a monthly short-term estimation.

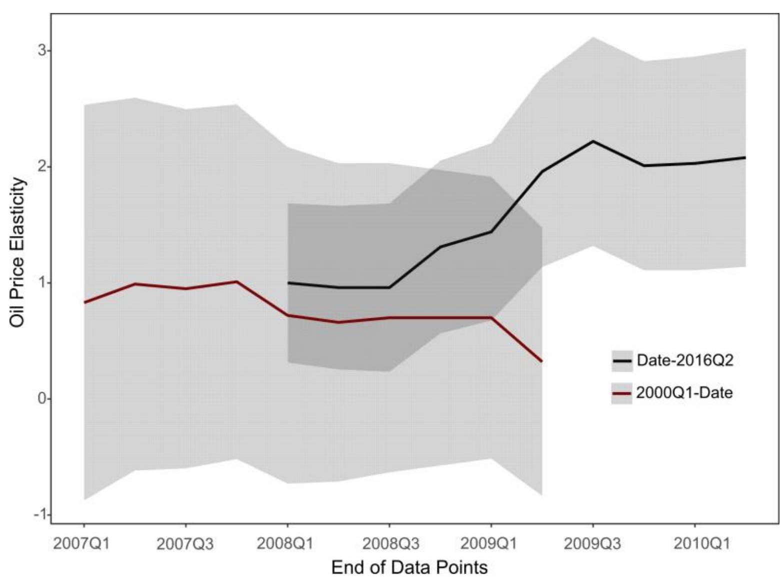

Figure 10: The variation of oil price elasticity of tight oil drilling activities.

Table 4. Summary of the Studies on Tight Oil Supply Responsiveness to Energy Prices

		Drilling		Production/Reserve	
	Sample period	Oil Price	Gas Price	Oil Price	Gas Price
This Study	2000-2008	0.7	-0.08	0.16	-0.03
	2010-2016	2.03***	-0.5	0.53***	-0.05
Newell & Prest (2019)	2005-2015	1.63***	-0.69	0.3-1.1†	
Smith & Lee (2017)	2014/2016	0.6-1.0	-	0.3-0.5	
Bjørnland et al. (2017)	1986-2015	-	-	0.035‡	-

*** Significant at the 1 percent level. ** Significant at the 5 percent level.
† Deciphered from the simulation plot; 0.3 is the one-year elasticity and 1.1 is the 12-year elasticity.
‡ Short-term elasticity; Monthly frequency.

The insignificance of gas price elasticity is due to several reasons. The first reason is the lack of basic gas processing and transport infrastructure, which resulted in the on-site flaring of associated natural gas in fast-growing tight oil plays such as Bakken and Niobrara. About one-third of the associated natural gas produced from North Dakota (mainly from the newly developed Bakken shale) was flared in 2011 due to limited natural gas infrastructure [39]. The flared natural gas did not contribute a profit. To make it worse, the associated natural gas may increase the cost because of stricter environmental requirements and the cost of implementing new gas processing facilities. North Dakota's Industrial Commission requires at least 91% recovery of the associated gas as of 2020 [40]. Operators not meeting the gas capture goal will face production restrictions and even civil penalties. In places with better infrastructure, such as the Eagle Ford play in Texas, selling the associated natural gas is relatively easy. However, the value of the associated natural gas is much lower than that of oil. Therefore, a drilling decision is mainly determined by the price and value of oil.

4.2 Robustness and Sensitivity

Regression results might be sensitive to the selection of energy prices. The WTI crude oil price and Henry Hub natural gas price are commonly used in the literature due to their easy availability. However, they are the transaction prices in one specific location. They can reflect the general price trends in other locations but might be substantially different from the local transaction prices. Econometric modeling using uniform energy prices for all tight oil plays may yield different results. I test the sensitivity of prices by using the WTI oil price and Henry Hub gas price for all tight oil plays. Regressions show that the oil price elasticity is 2.36 in the uniform-price Case 1' for drilling activity and is 0.67 in Case 4' for production. Both of them are higher than the results in corresponding panel price cases, which are 2.03 in Case 1 and 0.53 in Case 4 (Table 5).

Table 5. Regression Results using Uniform Prices and Different Model Settings

	Price Sensitivity		Model Robustness		
Dependents	Case 1'	Case 4'	Case 7	Case 8	Case 9
	2010-2016	2010-2016	2010-2016	2010-2016	2010-2016
lag(GasPrice, 1)	-0.32	-0.03	-0.09	-0.09	-0.09
	'(0.24)	'(0.08)	'(0.18)	'(0.19)	'(0.18)
lag(GasPrice, 2)	-0.13	-0.08	-0.3	-0.3	-0.3
	'(0.23)	'(0.08)	'(0.18)	'(0.18)	'(0.18)
lag(GasPrice, 3)	-0.39	-0.04	-0.12	-0.12	-0.12
	'(0.24)	'(0.09)	'(0.18)	'(0.18)	'(0.18)
lag(OilPrice, 1)	1.29***	0.16	1.05***	1.03***	1.05***
	'(0.30)	'(0.11)	'(0.23)	'(0.26)	'(0.23)
lag(OilPrice, 2)	1.22***	0.28***	1.04***	1.03***	1.05***
	'(0.29)	'(0.10)	'(0.26)	'(0.25)	'(0.24)
lag(OilPrice, 3)	-0.15	0.23**	-0.03	-0.03	-0.03
	'(0.31)	'(0.11)	'(0.28)	'(0.24)	'(0.24)
lag(Cost, 1)	0.34	0.38	0.05		
	'(1.10)	'(0.39)	'(1.09)		
lag(House, 1)	0.63	-0.99		-0.39	
	'(2.26)	'(0.83)		'(2.22)	
Sum.GasPrice	-0.84	-0.16	-0.51	-0.50	-0.51
	'(0.41)	'(0.15)	'(0.32)	'(0.32)	'(0.31)
Sum.OilPrice	2.36***	0.67***	2.06***	2.03***	2.07***
	'(0.52)	'(0.19)	'(0.44)	'(0.44)	'(0.41)
F	4.94	4.26	4.96	4.97	5.7
p-value	0	0	0	0	0
R-Squared	0.19	0.2	0.17	0.17	0.17
N	205	159	205	205	205

Notes: Sum.GasPrice and Sum.OilPrice are the computed long-term elasticity; Standard errors in parentheses. 2010-2016: 2010Q1-2016Q2; Q1: the first quarter of a year. Cases 1' and 4' use the same energy prices for all plays. Cases 7-9 use different model settings.
*** Significant at the 1 percent level. ** Significant at the 5 percent level.

The model setting is another factor influencing estimation results. Cases 7-9 are designed to test the robustness of model settings. Case 7 excludes the house price index, Case 8 excludes the cost index, and Case 9 excludes both. The estimated oil price elasticity varies from 2.03 to 2.06, which is consistent with the base case result (Case 1). The gas price elasticity is insignificant in all three cases, which is the same as in the base case. In general, the regression results are robust to the selection of control variables.

4.3 Forecast of Tight Oil Supply under the Coronavirus Pandemic

I use the estimated oil price elasticity in Case 4 and the real oil price and production data in 2001 as initial values to simulate the historical tight oil production. Regression between the actual production data and the simulated production in 2010Q1-2020Q1 shows a linear relation with a coefficient of 1.02 (Equation 3, Fig. 11a), which is close to 1. Therefore, using the estimated model to predict tight oil production is reliable.

$$Prod_{Real} = 0.13 + 1.02 * Prod_{Forecast} \qquad R^2 = 0.99 \qquad (3)$$

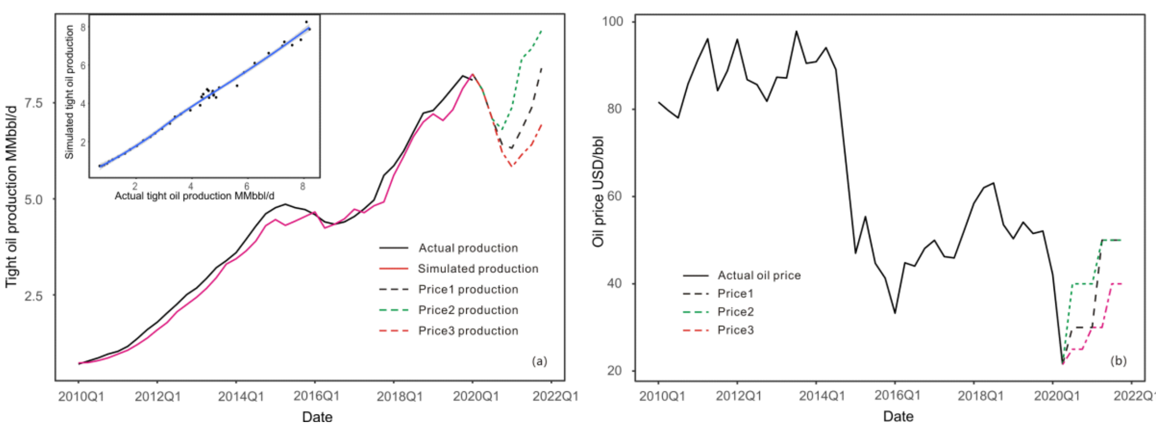

Figure 11. **(a)** Simulated tight oil production in 2010Q1-2020Q1 and forecasted tight oil production under three price models in 2020Q2-2021Q4. The insert is the regression between simulated production and actual production; **(b)** Real WTI spot oil price in 2010Q1-2020Q1 and three price models in 2020Q2-2021Q4.

Due to the influence of COVID-19, the oil price declined from about 50 USD/bbl in 2019 to less than 30 USD/bbl in 2020Q2 (Fig. 11b). If the pandemic lasts more than one year, the oil price could stay at low levels for a long time. Three price models are designed to simulate the possible influence of COVID-19. Price model 1 (PM-1) assumes an oil price of 30 USD/bbl from 2020Q3 to 2021Q1, which increases to 50 USD/bbl in 2021Q2 (Table 6, Fig.11b). Model 2 (PM-2) assumes that the global economy recovers in the second half of 2020 and the oil price increases to 40 USD/bbl in 2020Q3-2021Q1 and further to 50 USD/bbl in 2021Q2. Model 3 (PM-3) assumes a severe economic situation with oil prices of 25 USD/bbl in the second half of 2020, 30 USD/bbl in the first half of 2021 and 40 USD/bbl in the second half of 2021.

The simulated tight oil production decreases from 8.1 MMbbl/d in 2020Q1 to 6.3 MMbbl/d in 2021Q1 under PM-1, to 6.8 MMbbl/d in 2020Q4 under PM-2, and to 5.8 MMbbl/d in 2021Q1 under PM-3 (Fig.11a). Tight oil production is projected to increase again when oil prices recover.

Table 6. Oil Price Models used for Tight Oil Production Forecast.

Date	Price 1	Price 2	Price 3
2019.4	52	52	52
2020.1	42	42	42
2020.2	22	22	22
2020.3	30	40	25
2020.4	30	40	25
2021.1	30	40	30
2021.2	50	50	30
2021.3	50	50	40
2021.4	50	50	40

Notes: Oil prices before 2020Q2 are the same for all three models.

5. Discussion

5.1 Will the Low Oil Price Deter Tight Oil Development?

The 2.0 oil price elasticity for tight oil drilling and the 0.5 oil price elasticity for tight oil production shows that oil price has a substantially different impact on drilling activities versus oil production. During the 2014 oil price collapse, the WTI crude oil price declined 60% while the number of new tight oil wells declined 80% and the total tight oil production declined only 12%. In addition to the difference in elasticity, the response time is also different. The number of new wells declined after one quarter of a price decline, whereas the production started to decline after almost one year of the price drop (Fig. 3).

A major reason causing the differential responsiveness is the strong influence of legacy production, which is the output from existing wells. Legacy production is large in quantity. It accounts for more than 90% of the total tight oil production in Bakken and more than 80% in Eagle Ford in 2007-2019 (computed from data in [41]; Fig.12). Therefore, the price responsiveness of legacy production dominates the responsiveness of total tight oil production.

To understand the influence of oil price on legacy production, we need to separate the full-cycle breakeven cost from the half-cycle breakeven cost for petroleum extraction [13]. The full-cycle breakeven cost includes both capital expenditure (CAPEX) and operating expenses (OPEX), which were estimated to be more than 60 USD/bbl for tight oil in 2014 [42]. The half-cycle breakeven cost during production includes the OPEX only and was estimated to be 15-37 USD/bbl in 2014 [43]. Since the CAPEX becomes a sunk cost once a well starts to produce, the difference between OPEX and oil price is a major factor for management decisions in legacy production: as long as the OPEX is lower than oil price, a well will not be shut in. The oil price in 2014 was 60-106 USD/bbl, which was higher than the OPEX. Therefore, the legacy production did not decline at all in the Bakken formation in 2014 (Fig. 12a). The oil price reached about 30 USD/bbl in 2016, lower than the OPEX of some high-cost wells. However, the technical complexity and uncertainty, as well as the economic risk of closing a tight oil well, limited the closure to a small scale [44]. In addition, the decline rate of tight oil wells is low after the first three years. Tight oil wells maintain relatively stable production for more than ten years and their productivity is higher than most conventional oil wells [11]. This further supports the profitability and unresponsiveness of the long-lasting production tail of tight oil.

The production from new wells is more responsive to energy prices because they are determined by the drilling of new wells, which is elastic to the change in oil prices. Figure 12 shows that the decline of new production is much higher than that of legacy production. The new production decreased 75% in 2014-2016 for both plays while the legacy production declined only 17% in Bakken and 29% in Eagle Ford. The high weight of legacy oil, together with its unresponsiveness to energy prices, led to the inelastic feature of tight oil production.

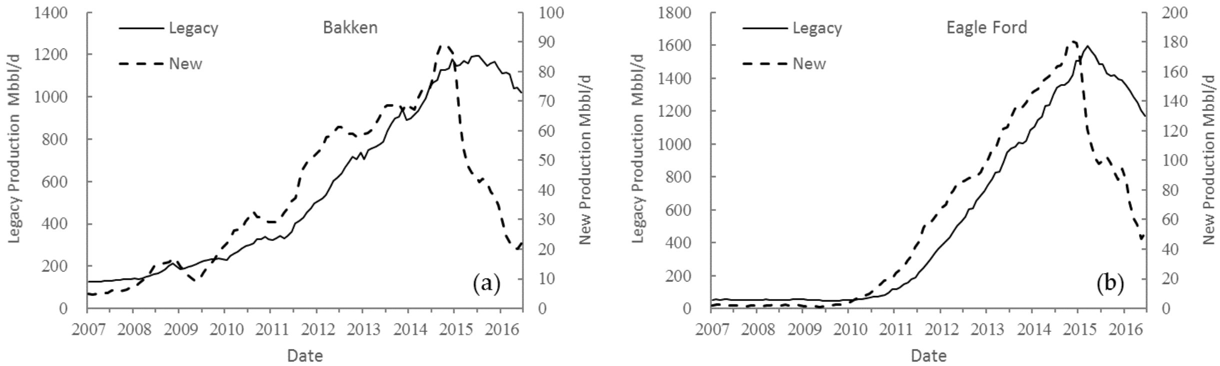

Figure 12: Trends of new and legacy tight oil production in the **(a)** Bakken and **(b)** Eagle Ford plays. Data is from [41].

Due to the impacts of COVID-19, the WTI spot oil price declined to 22 USD/bbl in 2020Q2 (average price of April and May only) [5], which was even lower than that in the 2014 price collapse. However, the operating expenses have declined too, and some companies could produce at a cost of less than 10 USD/bbl [45].

Worries about running out of storage capacity have led to expectations of large-scale shut-in of existing wells, not only stripper wells with very low productivity, but also high productivity wells [44,46]. However, the working storage capacity in the United States is 61% full [47] as of May 2020, which leaves a lot of room for oil surplus. In addition, the storage build-up rate is about 2.4 MMbbl/d from March to May 2020, whereas the predicted decline for tight oil production is up to 2.3 MMbbl/d in 2021Q1, which will substantially alleviate the stock pressure. Also, as the world economy gradually recovers, so will the demand for oil; therefore, a large-scale shut-in of existing tight oil wells is not likely to happen. However, the drilling of new wells will be limited at low oil price levels, based on the price elasticity estimated in Section 4.1.

5.2 Will Tight Oil Become the New "Swing Producer"?

The 2014 price collapse was triggered by the U.S. tight oil boom but was used by OPEC as a price deterrence policy to force out tight oil players. During the collapse, there was a discussion on whether U.S. tight oil was ready to assume the "swing producer" role held by OPEC since the 1970s. Some researchers supported the new role of tight oil [48], whereas others believed that tight oil did not fit the "traditional notion of a swing producer" [11]. An indisputable answer depends largely on the definition of "swing producer", which, however, is not clear [11,48,49].

In order to clarify the meaning of “swing producer”, I conducted a thorough literature study. The phrase appeared in the literature for the first time in 1974 when it was used to describe the role of Saudi Arabia in oil supply [50]. The timing was right after the OPEC price control in 1973. The number of records with “swing producer” plus “oil” increased from 13 in the 1970s to 1260 in the 2010s (Fig. 13). A detailed examination of articles shows that “swing producer” is a synonym for “residual supplier”. Authors used both terms in one paper [51,52], and in earlier times the word “residual supplier” was more often used (Fig. 13). The term “swing producer” has become favored since the 1990s (Fig. 13). The number of records containing “swing producer” and “oil” is close to the number of records searched using “swing producer” only, which indicates that the terminology is specific to describe oil-related issues (Fig. 13). The fraction between “residual supplier” + “oil” and “residual supplier” is in the range of 0.5 to 0.7. A detailed survey shows that the term “residual supplier” has been used to describe agricultural commodities since the 1950s [53]. Therefore, the term “swing producer” is derived from “residual supplier” and is its synonym in the oil market.

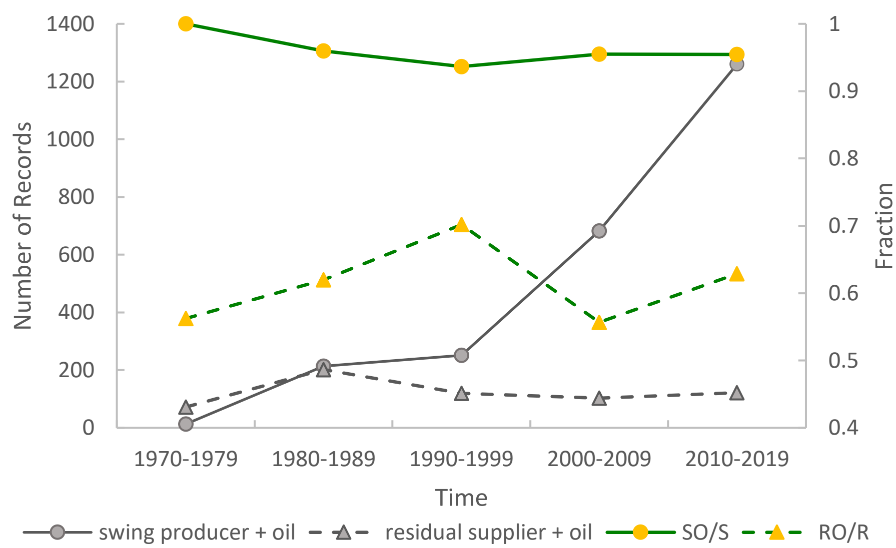

Figure 13: History of the number of papers containing “swing producer” + “oil” and “residual supplier” + “oil”. The number of records is obtained in Google Scholar using different keywords. “swing producer” + “oil”: the key words are “swing producer” and “oil”; “residual supplier” + “oil”: the keywords are “residual supplier” and “oil”; SO/S: the ratio of the number of records between “swing producer” + “oil” and “swing producer”; RO/R: the ratio between “residual supplier” + “oil” and “residual supplier”.

Although a clear definition of "swing producer" is not found in the literature, some studies describe its characteristics or criteria. Griffin and Teece [52] described Saudi Arabia as a "swing producer" or "balancing wheel" "absorbing demand and supply fluctuations in order to maintain the monopoly price". Adelman [15] thought that OPEC as a whole acted as a residual supplier for the world oil market by setting a monopoly oil price and restricting output. But he also mentioned that Saudi Arabia was the "swing producer" without clearly defining the term. He probably meant that OPEC was the residual supplier for the world and Saudi Arabia was the residual supplier for OPEC. Libecap [51] went further to give quantitative criteria. He believed that a swing producer's production should be cointegrated with the total demand. By conducting cointegration analysis, the author screened out non-swing producers. Dahl and Yücel [54] used the ratio of standard deviation (σ) and mean (μ) of oil production, i.e. σ/μ, to measure the proportionate change of production. If the ratio of a country was higher than OPEC's proportionate change, it was a candidate for swing producer. Examination of the literature shows that a "swing producer" is the residual supplier of the crude oil market, which has the following characteristics:

1) the role of a swing producer is to maintain higher-than-competitive market prices by constraining production, either proactively or passively;

2) its production cost is usually lower than the average cost;

3) its full-capacity production can influence the market price significantly;

4) other producers are either not limited in production or receive higher production quotas, with the "swing" producer supplying the residual demand.

According to these criteria, the low-cost oil in Texas was a swing producer for the interstate cartel of the United States in the 1930s; OPEC as a whole was a swing producer for the world oil market and Saudi Arabia was the swing producer within OPEC in the 1970s. Tight oil does not satisfy the criteria of a "swing producer". Its cost is higher than conventional oil and no entity is trying to regulate tight oil production by force or through agreement. The Railroad Commission of Texas declined a proposal to cut production in response to the price decline during the pandemic in May 2020 [55]. Instead, it was OPEC that led the production control in 2016 [56] and 2020 [57]. Therefore, the role of swing producer still belongs to conventional-oil producing countries rather than the high-cost tight oil.

6. Conclusion

This study analyzes the influence of low oil prices on tight oil supply by estimating the oil and gas price elasticities for tight oil drilling activity and tight oil production using econometric methods. The regression results show that 1) the oil price elasticity of tight oil drilling increased from insignificant in 2000-2008 to 2.0 in 2010-2016; 2) the oil price elasticity for tight oil production increased from insignificant to 0.5 in the same periods; and 3) neither drilling activities nor production was responsive to gas prices in either period. Forecasts using the estimated econometric parameters show that tight oil production could decrease by 1.3-2.3 MMbbl/d during the pandemic-induced recession, which is 16-28% of the productivity in 2020Q1.

COVID-19 imposes unprecedented challenges on the oil and gas industry. Controlling production from tight oil wells faces even greater difficulty compared to conventional wells due to the horizontal well design and complex liquid flow mechanism. Continuous studies focusing on the supply of tight oil during the pandemic will provide valuable knowledge for our understanding of the world oil market.

Nomenclature

bbl/d: barrels per day

BLS: U.S. Bureau of Labor Statistics

COVID-19: Coronavirus disease 2019

CPI: consumer price index

EIA: U.S. Energy Information Administration

GOR: gas-to-oil ratio

HPI: house price index

IPGD: initial production of gas per day

IPOD: initial production of oil per day

MD: measured depth

MMbbl/d: million barrels per day

NGI: Natural Gas Intelligence

NGL: natural gas liquid

OECD: Organisation for Economic Co-operation and Development

OPEC: Organization of the Petroleum Exporting Countries

PPI: producer price index

SPI: Shale price indices

US: United States

USD/bbl: US dollars per barrel

USD/MMBtu: US dollars per million British thermal units

WTI: West Texas Intermediate

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Appendix

Table A1. Methods of Computing Crude Oil Prices for each Tight Oil Play

Reservoir	Period (year, quarter)	Method
Bakken	2000 Q1 – 2009 Q4	North Dakota*
Bakken	2010 Q1 – 2016 Q1	North.Dakota.Light.Sweet +
Bakken	2016 Q2 – 2016 Q3	ND
Barnett	2000 Q1 – 2016 Q3	Texas *
Bone Spring	2000 Q1 – 2016 Q3	New Mexico *
Eagle Ford	2000 Q1 – 2010 Q4	Texas *
Eagle Ford	2011 Q1 – 2016 Q3	Eagle Ford Condensate +
Granite Wash	2000 Q1 – 2007 Q1	Texas *
Granite Wash	2007 Q2 – 2016 Q3	North.Texas.Sweet +
Niobrara	2000 Q1 – 2016 Q3	Colorado *
Wolfcamp	2000 Q1 – 2016 Q3	WTI
Woodford	2000 Q1 – 2016 Q3	Oklahoma *
Yeso-Glorieta	2000 Q1 – 2016 Q3	New Mexico *

Notes: * EIA first purchase price of crude oil; + Enterprise Products Partners L.P. crude oil price

Table A2. Methods of Computing Associated Natural Gas Prices for each Tight Oil Play

Reservoir	Period (year, quarter)	Method
Bakken	2000 Q1 – 2016 Q3	Hentry Hub
Barnett	2000 Q1 – 2009 Q4	Average of NGPL TexOK and NGPL midcontinent
Barnett	2010 Q1 – 2016 Q3	Barnett
Bone Spring	2000 Q1 – 2016 Q3	Average of Waha, Transwestern, El paso permian prices
Eagle Ford	2000 Q1 – 2009 Q4	Average of NGPL S.TX and Transco Zone 1
Eagle Ford	2010 Q1 – 2016 Q3	Eagle Ford
Granite Wash	2000 Q1 – 2009 Q4	Average of NGPL midcont., OGT, Enable W., Panhandle E., Southern Star, ANR SW
Granite Wash	2010 Q1 – 2016 Q3	Granite Wash
Niobrara	2000 Q1 – 2009 Q4	Average of Kern River, Northwest Wyoming, Opal, and Cheyenne Hub
Niobrara	2010 Q1 – 2013 Q3	West Green River Basin
Niobrara	2013 Q4 – 2016 Q3	West Niobrara
Wolfcamp	2000 Q1 – 2009 Q4	Average of El Paso Permian, Transwestern, and Waha Hub
Wolfcamp	2010 Q1 – 2013 Q3	Barnett
Wolfcamp	2013 Q4 – 2016 Q3	Permian
Woodford	2000 Q1 – 2009 Q4	Average of NGPL TexOK, NGPL midcont., OGT, Enable W., Panhandle E., S. Star
Woodford	2010 Q1 – 2016 Q3	Average of ArkomaWoodford and CanaWoodford
Yeso-Glorieta	2000 Q1 – 2016 Q3	Waha hub

Table A3. Weighting Methods to Compute the HPI for each Tight Oil Play in 2000-2016

Reservoir	Weight
Bakken	0.1MT+0.9ND
Barnett	TX
Bone Spring	0.1TX+0.9NM
Eagle Ford	TX
Granite Wash	0.1OK+0.9TX
Niobrara	CO
Wolfcamp	0.14NM+0.86TX
Woodford	OK
Yeso-Glorieta	NM