1 Upcoming

Our main objective is to complete a draft by December 15 for submission to the department's 3rd year paper competition.

2 Overview

Up until now, we've thought of this as a static problem: firms choose production and emissions rate instantaneously given prevailing costs and prices. However, there are important dynamic considerations that we've been ignoring:

- Waha spot market prices are the product of both short-run and long-run factors. Congestion varies stochastically due to midstream equipment failures and variation in aggregate gas production. This congestion pushes down Waha prices but is generally short-lived. Waha prices also move with Henry prices, which reflect aggregate demand and supply and are generally more stable.
- Emissions are the result of short-term (venting, flaring), medium-term (maintenance, leak repair), and long-term (drilling new wells, investments in less-leaky equipment) decisions.

Figure 1: Spot market prices at Henry and Waha Hubs

Ignoring the difference between short- and long-run margins can lead to confusion. For instance, a decrease in the Waha price could result from either a) a decrease in aggregate gas demand, or b) increased congestion. In the former case, producers expect lower prices going forward and should thus respond by drilling fewer wells, reducing emissions. In the latter case, producers expect prices to rebound quickly and so they should not adjust the path of future production. Instead, they should respond by flaring/venting a larger share of their gas, increasing emissions.

When we regress emissions on Waha prices, we aggregate these two, contrasting effects. This may explain why Waha prices are not strongly correlated with emissions but are positively correlated with the Waha basis (Figure 4). However, when we limit our focus to flaring/venting, we get consistent, significant estimates for both Waha basis and Waha prices (Figures 2, 3)

3 Model

3.1 Dynamic production decision

We present a dynamic model of producer production and emissions decisions. Each period, the producer chooses the number of new wells to develop a_t, and its emissions rate for gas production e_t. It chooses a_t and e_t to maximize current profits plus the discounted stream of expected future profits.

Let $\Omega_t = (q_t, p_t, u_t)$ be a producer's state space in period t, where q_t is the level of oil production from *existing* wells, $p_t = (p_t^o, p_t^g)$ are the oil and gas prices in the period, and u_t is the utilization rate of gas pipelines. We assume that each producer is small and does not influence u_t. Wells drilled in period t begin producing in period $t+1$. Production from a well decays exponentially at rate γ. The level of gas production, αq, follows deterministically from the level of oil production, according to the gas-to-oil ratio of the wells, α.

Let r be the oil produced in a well's first period of production (i.e. the period after it is drilled). The process of drilling a well results in emissions that are proportional to the well's productivity, with multiplier f. These emissions occur in the period that the well is drilled. We allow for a tax τ on methane emissions, which result from both well drilling and from producer decisions to release share e of the gas they produce.

The value function for the producer is then given by

$$
\begin{aligned}
V(\Omega_t) &= \max_{a_t, e_t} \pi(e_t, \Omega_t) - c_t(a_t) - \tau f r a_t + \beta \mathbb{E}[V(\Omega_{t+1}) | a_t, \Omega_t] \\
&= \max_{a_t, e_t} \pi(e_t, \Omega_t) - c_t(a_t) - \tau f r a_t + \beta \int V(\Omega_{t+1}) \mathbb{P}(\Omega_{t+1} | a_t, \Omega_t)
\end{aligned}
$$

subject to

$$
\begin{gathered}
q_t = \gamma q_{t-1} + r a_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim \mathbb{N}(0, \sigma^2), \\
a_t \geq 0, \\
0 \leq e_t \leq 1
\end{gathered}
$$

where, ignoring the time subscripts,

$$
\pi(e, \Omega) = \underbrace{p^o q - c_o(q)}_{\text{oil profit}} + \underbrace{p^g \left[(1-e)\alpha q\right]}_{\text{gas revenue}} - \underbrace{c_g(e, \alpha q; u)}_{\text{gas capture/marketing costs}} - \underbrace{\tau e \alpha q}_{\text{emissions tax}} .
$$

We further decompose c_g into the cost of abatement and the cost of marketing the gas:

$$
c_g(e, \alpha q; u) = \underbrace{c_a(e) \cdot \alpha q}_{\text{abatement cost}} + \underbrace{c_m(u) \cdot (1-e)\alpha q}_{\text{marketing cost}} .
$$

A key feature of this framework is that emissions decisions are static choices that respond to prices, whereas production *levels* from existing wells are insensitive to current prices. The optimal emissions rate from existing wells is given by

$$
\underbrace{c_m(u) - c_a'(e^*)}_{\text{marginal benefit}} = \underbrace{p_g}_{\text{marginal cost}} .
$$

Total emissions in period t are given by $eq_t + fra_t$ and the emissions rate is given by $(e + fra_t)/q_t$.

Another key feature of this model is that it allows for differing intertemporal responses to changes in price and changes in marketing costs. If shocks to transmission costs are more transitory than price shocks, then a_t will respond differently to the two shocks. If we augment the model as suggested in modeling question 7 below, then this implies that emissions are higher from a transmission cost shock than an equally-sized price shock (since a_t is lower in the case of a price shock).

3.2 Identification

In our data, we directly observe α, γ, and σ^2. We need to recover the time-varying cost of investment in new wells $c_t(\cdot)$, the cost of abatement $c_a(\cdot)$, and the marketing cost $c_m(\cdot)$. The latter two costs can be estimated offline in the static framework. The time-varying investment cost is estimated within the model, either using data on rig day rates that allow us to observe the vast majority of the investment cost directly, or by making a functional form assumption.

We can either attempt to estimate the emissions multiplier f associated with a new well using our data, or by borrowing an estimate from the engineering literature.

3.3 Modeling Questions

1. Should we model oil stocks as a depletable resource? Anderson, Kellogg, and Salant (2018) describe oil production as a "keg-tapping problem" rather than a "pie-eating problem." production on the intensive margin for existing wells?

2. Anderson, Kellogg, and Salant (2018) present a continuous time model. Is this necessary here as well?

3. Anderson, Kellogg, and Salant (2018) assume a marginal cost of extraction of zero. Should we make this simplification as well? In this case, that means setting $c_o(q) = 0$.

4. Should we make functional form assumptions on the cost functions? For example, we could assume that $c(a_t) = ca_t$ or $c(a_t) = \beta a_t^2$.

5. We are not currently modeling shut-ins. Temporary shut-ins happen but are rare. Do we need to incorporate this as an additional decision the firm can make, where a shut-in comes at a high cost?

4 Empirics

4.1 Venting + flaring, total emissions, and Waha basis vs. Waha prices

Thanks to newly acquired data on producer reports of how much gas they flare and vent each month, we're able to examine this margin of producer behavior directly. In Figures 2 and 3, we see that firms flare/vent more when Waha prices are low and the Waha basis is high. This contrasts with total emissions (Figure 4), which have a clear correlation with the Waha basis but not the Waha price itself.

Figure 2: Producer-reported venting and flaring vs. Waha basis

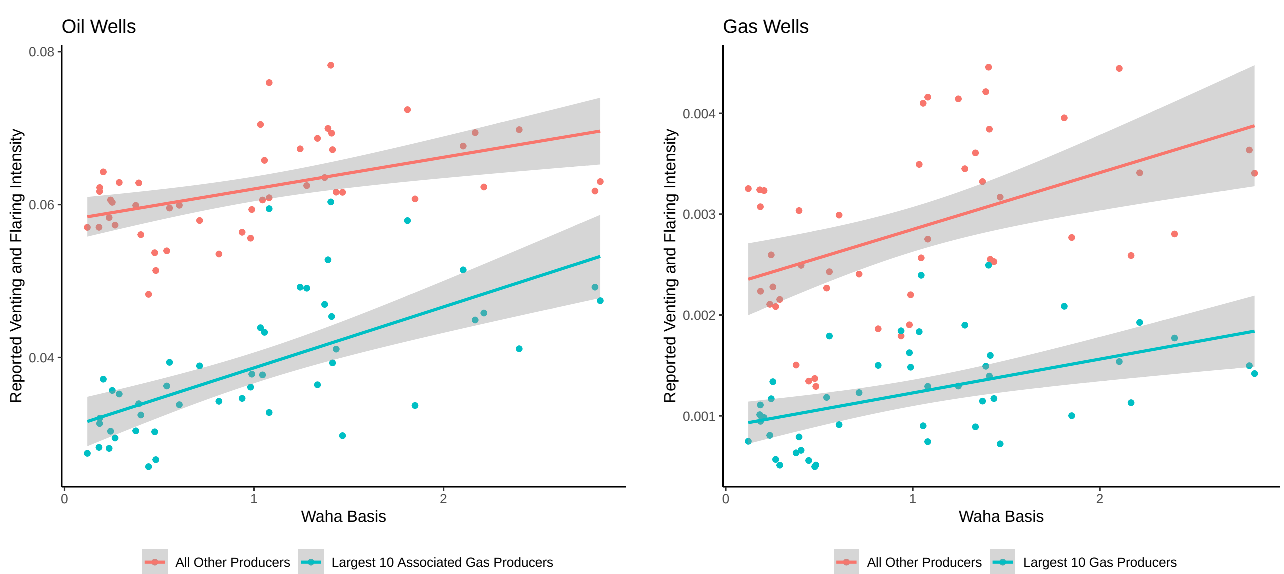


Figure 3: Producer-reported venting and flaring vs. Waha prices

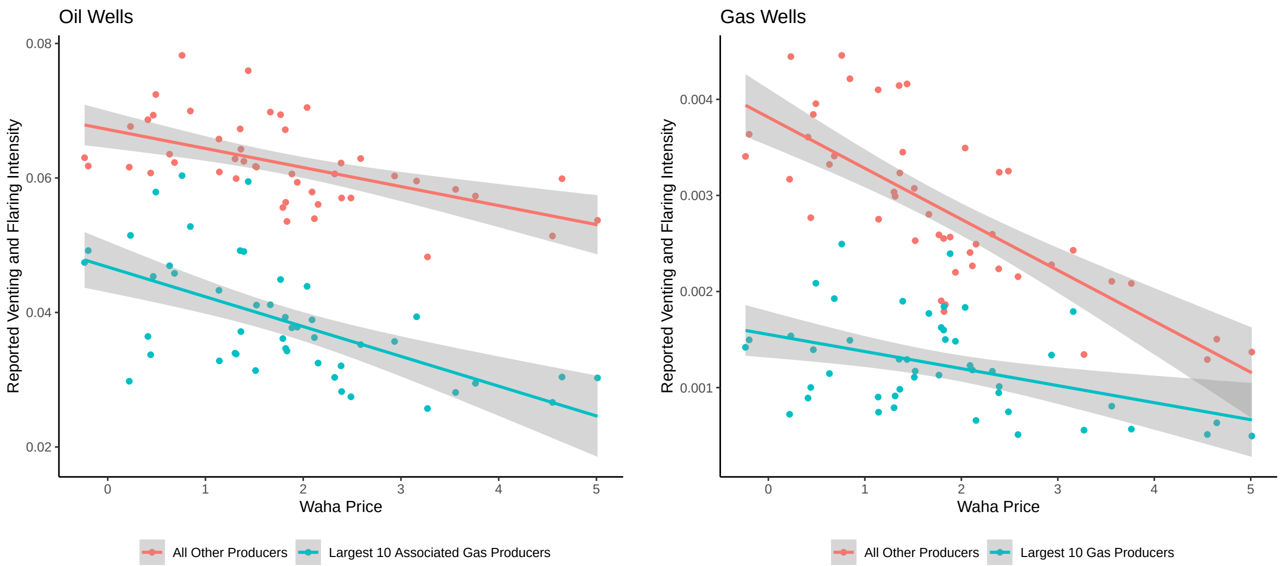
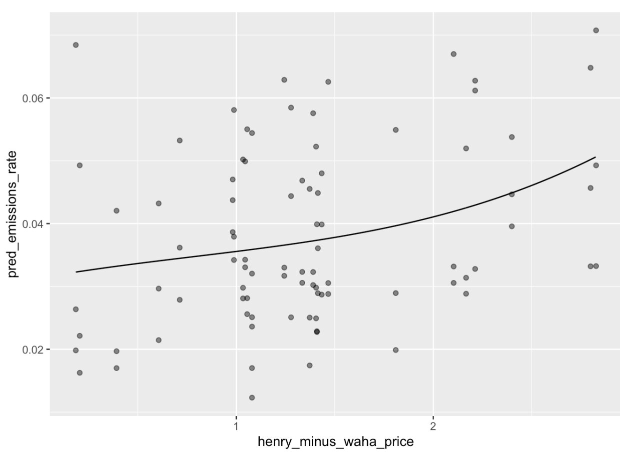
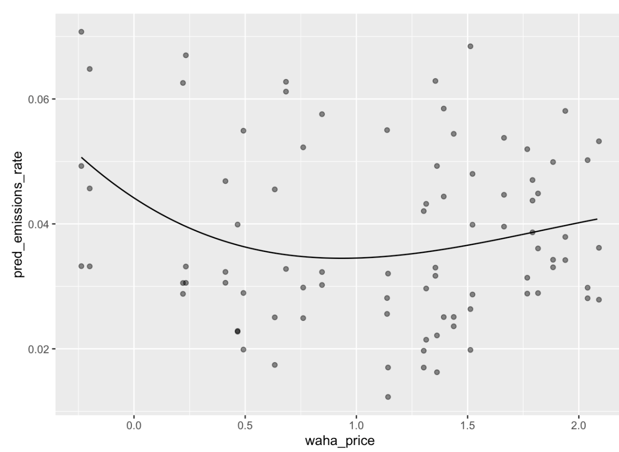


Figure 4: Emissions

(a) Waha basis



(b) Waha price



4.2 Revenue shares

We use severance tax data from Enverus to get a sense of how much revenue producers raise from oil vs. gas. Producers make monthly reports of their sales volume and values for tax purposes. For this analysis, we aggregate producer-level sales figures for 2018.

In Table 1, we see that even the top gas producers raise well over half of their revenues from oil. The total gas volume captured in this dataset is about 2.3 trillion cubic feet. The top gas producer by volume, Pioneer Natural Resources USA, accounts for about 10% of this total. Even so, Pioneer's gas sales amount to only about 14% of its total gas and oil sales for 2018. Across all producers in the dataset, the median oil value share is 98% and the mean is 78%.

Table 1: Oil Revenue Shares for Top Gas Producers, 2018

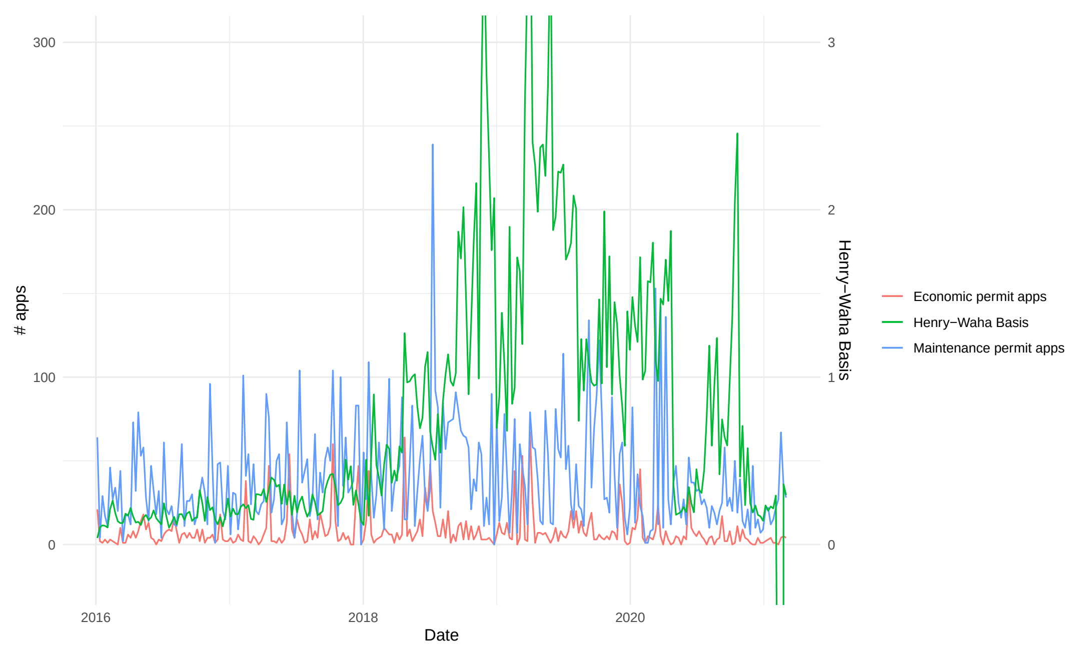
Producer	Gas Volume (BCF)	Oil Volume (MMBbl)	Oil Revenue Share
PIONEER NATURAL RESOURCES USA, INC.	270.41	74.45	0.8612
APACHE CORPORATION	226.77	30.34	0.7048
CHEVRON U.S.A. INC.	141.39	29.08	0.7083
XTO ENERGY INC.	124.38	52.29	0.8738
ANADARKO E&P ONSHORE LLC	107.23	25.68	0.8083
COG OPERATING LLC	106.42	26.26	0.7743
PARSLEY ENERGY OPERATIONS, LLC	71.43	22.77	0.8365
ENERGEN RESOURCES CORPORATION	71.05	27.73	0.8715
OCCIDENTAL PERMIAN LTD.	64.04	33.82	0.9434
LAREDO PETROLEUM, INC.	59.35	12.35	0.7793

Notes: Sales data from Enverus. We aggregate sales volumes and values by reported seller name for all observations in 2018. We present here the data for the top 10 gas producers by volume in 2018. We calculate the oil value share to be the ratio of oil sales value to the sum of oil and gas value for each producer.

4.3 Permit requests

We have data from the Texas Railroad Commission on permits for flaring/venting. We separate permit requests by how producers justify their request. We categorize as "economic" any request that includes words such as "cost", "purchaser", "economic", or "revenue". We categorize as "maintenance" any request including words such as "maintenance", "repair", "broken", or "upset". In Figure 5, we plot the number of requests in these two categories by the date of the request, alongside the Henry-Waha basis.

Figure 5: Flaring permit requests and Henry-Waha basis



A Appendix: Figures and Tables

Figure 6: Production by basin

(a) Gas production (b) Oil production

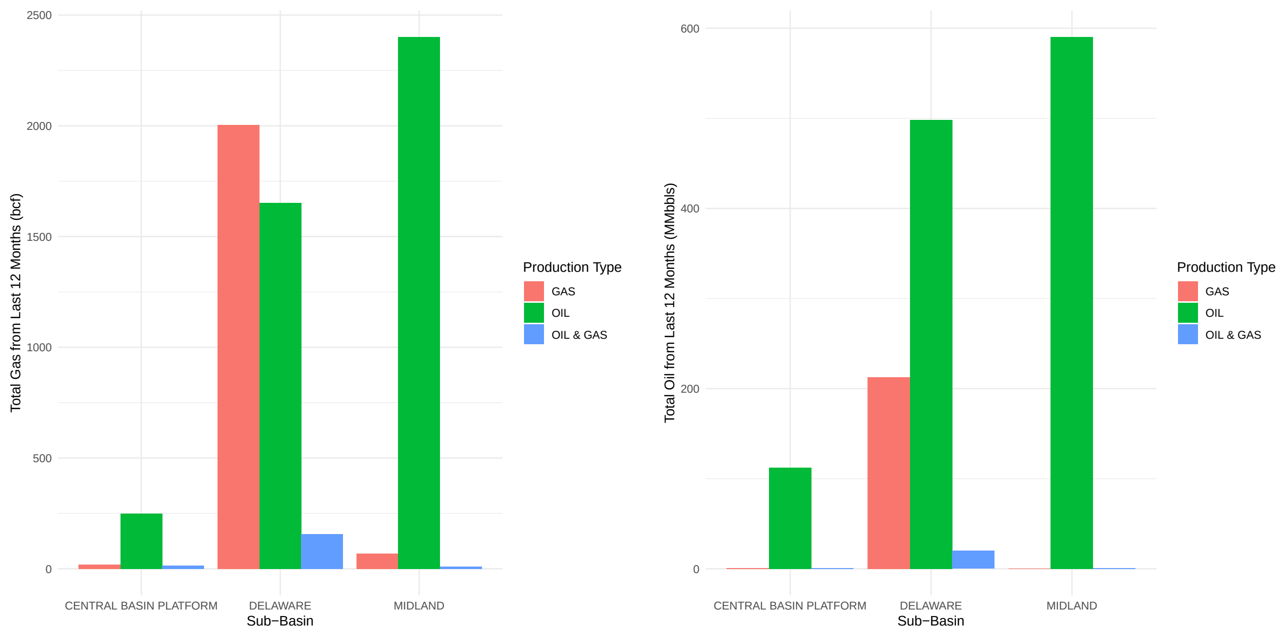


Table 2: Methane Emissions, Prices, and Production

	Dependent variable:			
	log(emissions)			
	All	Midland	Central	Delaware
	(1)	(2)	(3)	(4)
Waha Hub Price	0.036	-0.003	0.007	0.055
	(0.049)	(0.059)	(0.035)	(0.058)
Henry - Waha Hub Price	0.084^{*}	0.137^{**}	0.096^{**}	0.012
	(0.049)	(0.056)	(0.039)	(0.059)
Cushing Spot Oil Price	-0.004^{**}	-0.003	0.001	-0.009^{***}
	(0.002)	(0.002)	(0.002)	(0.003)
log(Oil Production)	0.985	-1.552^{*}	-0.423	3.620^{**}
	(1.195)	(0.801)	(0.755)	(1.400)
log(Gas Production)	-0.994	1.132	1.388	-3.405^{***}
	(1.014)	(0.757)	(0.908)	(1.286)
log(New Wells)	0.215	0.136	0.013	0.550^{**}
	(0.159)	(0.340)	(0.069)	(0.268)
log(Lagged New Wells)	0.040	0.299	-0.048	-0.182
	(0.161)	(0.347)	(0.070)	(0.270)
Constant	1.150	4.507	-16.274^{**}	-0.710
	(4.859)	(5.247)	(7.502)	(4.480)
Observations	127	127	127	127
R^2	0.316	0.277	0.238	0.325
Adjusted R^2	0.275	0.235	0.194	0.286
Residual Std. Error (df = 119)	0.211	0.242	0.184	0.268
F Statistic (df = 7; 119)	7.841^{***}	6.517^{***}	5.323^{***}	8.200^{***}

Notes: An observation is a week. Emissions are in log teragrams per annum (Tg/a). Prices reflect the average of prices over the week. Oil and gas production and new wells are measured monthly. Oil and gas production are in sbarrels and thousands of cubic feet (Mcf), respectively. Flared volume is measured in billions of cubic feet.
$^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table 3: Flared Gas, Prices, and Production

	Dependent variable: log(flared gas)		
	All	Midland	Delaware
	(1)	(2)	(3)
Waha Hub Price	0.006^{*}	0.013^{***}	0.001
	(0.003)	(0.004)	(0.003)
Henry - Waha Hub Price	0.162^{***}	0.295^{***}	0.178^{***}
	(0.031)	(0.038)	(0.033)
Cushing Spot Oil Price	-0.001	0.002	-0.009^{***}
	(0.002)	(0.002)	(0.002)
log(Oil Production)	6.658^{***}	7.435^{***}	1.729
	(1.014)	(0.713)	(1.141)
log(Gas Production)	-5.290^{***}	-4.605^{***}	-2.351^{**}
	(0.781)	(0.530)	(1.020)
log(New Wells)	0.277^{*}	-0.325	0.667^{***}
	(0.167)	(0.312)	(0.228)
log(Lagged New Wells)	-0.342^{**}	-0.241	-0.227
	(0.168)	(0.310)	(0.234)
Constant	-17.729^{***}	-41.084^{***}	11.849^{***}
	(3.889)	(3.637)	(1.996)
Observations	190	199	199
R^2	0.631	0.648	0.580
Adjusted R^2	0.617	0.636	0.564
Residual Std. Error	0.251 (df = 182)	0.331 (df = 191)	0.282 (df = 191)
F Statistic	44.553^{***} (df = 7; 182)	50.320^{***} (df = 7; 191)	37.660^{***} (df = 7; 191)

Notes: An observation is a week. Outcome variable is the volume of flared gas, based on VIIRS observations and calibrated to match administrative data. Prices reflect the average of prices over the week. Oil and gas production and new wells are measured monthly and interpolated to the week level. Oil and gas production are in barrels and thousands of cubic feet (Mcf), respectively.
$^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table 4: Oil prices, drilling, and production

	Dependent variable:		
	log(sum_spuds)	log(Firstprod)	log(SUM.Monthly.Oil.)
	Spuds	First Prod	Bbl Oil
	(1)	(2)	(3)
Log(Cushing, Forward contract)	2.711^{***}	2.564^{***}	-1.731^{*}
	(0.810)	(0.534)	(0.881)
Log(Cushing, 3 month contract)	-2.443^{***}	-2.423^{***}	1.778
	(0.861)	(0.567)	(1.124)
Log(Henry spot price)	-0.226	-0.190^{*}	-0.210
	(0.163)	(0.109)	(0.194)
Basin = Midland	0.333^{***}	0.643^{***}	-1.147^{***}
	(0.081)	(0.053)	(0.087)
Production type = Oil			3.673^{***}
			(0.087)
Constant	4.105^{***}	4.414^{***}	12.527^{***}
	(0.601)	(0.395)	(1.319)
Observations	320	318	396
R^2	0.099	0.358	0.836
Adjusted R^2	0.088	0.350	0.834
Residual Std. Error	0.721 (df = 315)	0.474 (df = 313)	0.862 (df = 390)
F Statistic	8.665^{***} (df = 4; 315)	43.678^{***} (df = 4; 313)	396.896^{***} (df = 5; 390)

Notes: An observation is a month. Prices reflect the average of prices over the month.
$^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$