Effects of State Taxation on Investment: Evidence from the Oil Industry[*]

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Abstract

We provide evidence that firms do not respond equally to output prices and taxes in the context of United States oil drilling. Econometrically, we find that a one dollar per unit increase in tax has at least 8 times as large an effect on drilling as a one dollar per unit decrease in the price of oil. Our theoretical model provides an explanation - a tax change only affects the returns to drilling in a single state, whereas a price change affects both the returns to drilling in a state and the opportunity cost of not drilling in other states. These results imply that inferring tax impacts from price-driven changes in marginal revenue can lead to incorrect estimates.

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1 Introduction

Understanding how economic agents respond to change in prices and taxes is important for informing policy decisions. Recent work has shown that consumers respond differently to prices and taxes (Li et al., 2014). Similarly, firm responses to price may differ from the response to tax rates. However, conventional economic models assume that firms respond to prices and taxes equally, typically by assuming that firms respond to marginal revenue, net of taxes. This assumption is made in settings including sector-agnostic production (Dharmapala et al., 2011; Best et al., 2015), oil production (Maniloff and Manning, 2017; Metcalf, 2018), banking (Albertazzi and Gambacorta, 2010), and trade (Hummels and Skiba, 2004). We test this assumption in the setting of oil production and find that US firms respond differently to state taxes and output prices.

Our empirical exercise is motivated by a theoretical model that highlights the importance of a production tax in influencing firm decisions. Our theoretical results show that changes in location-specific tax rates affect firms in qualitatively different ways than changes in output price. Empirically, we confirm that the responsiveness of oil drilling to taxes differs from the responsiveness to price. This difference is economically and statistically significant. Finally, we use the empirical estimates to simulate the effect of tax changes on state government revenue.

By exploring the effects of state oil production ('severance') taxes, we make two contributions to the literature on taxation and economic activity. First, we develop a theoretical model of drilling decisions in a multi-state setting with a common output price but spatially differentiated taxation. The theoretical model demonstrates that while both price and tax increases affect the revenue earned from drilling in a given state, a price change also affects the opportunity cost of drilling and leads to a different net effect. Therefore, it is necessary to separately estimate the impacts of oil price and severance tax rates on oil drilling activity.

Second, we use spatially and temporally detailed data on the location of oil wells to estimate how oil producers responded to severance taxes over a 30-year period in 91 oil reservoirs in 17 oil-producing states. Our core econometric results confirm the theoretical predictions and show that a one dollar increase in the price of oil leads to a 1 percent increase in wells drilled, but a one dollar increase in tax leads to at least an 8 percent decrease in wells drilled.

Our analysis provides timely and policy-relevant information for policymakers in states that partially depend on rents from oil production to fund government programs and initiatives. The recent fracking boom caused oil production to increase by 73 percent from 2005 to 2015[1], while revenue from oil and gas production increased to over 20 percent of tax receipts in the top ten revenue states (Weber et al., 2016). Proponents of increases in tax rates see opportunities to increase government revenue, especially during periods of high oil prices and activity. Conversely, opponents argue that increases in taxation will lead drilling companies to invest in neighboring states. Some states have chosen to subsidize drilling by foregoing severance tax revenue on certain wells in order to attract more drilling activity. For example, Oklahoma lawmakers reduced the state's severance tax on new horizontally-drilled wells to one percent for the first 48 months of production, which equated to $379 million in tax breaks in 2015 (Blatt, 2015).

While our estimates do not account for the long-run supply response to prices or taxes, they provide valuable information about how an important economic activity across many parts of the country responds to changes in state tax policy. The response to a change in tax paid per barrel of oil is inelastic, implying that an increase in the tax rate per barrel leads to increases in tax revenue. The policy implication is that state governments should use caution when considering the use of lower tax rates to attract more drilling from neighboring states.

In the remainder of this paper, section 2 reviews the relevant literature on taxation, in-

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[1] Authors' calculations using production data from the Energy Information Administration available at http://www.eia.gov.

vestment, and oil production. Section 3 describes a theoretical model of industry drilling decisions using a 2-location model. Section 4 discusses our econometric model and identification strategy used to test the theoretical hypotheses described in section 3. Section 5 reports data used in the empirical analysis. Section 6 presents results from estimating the effect of severance taxes on drilling. Then, in section 7, we apply our estimates to a policy scenario to examine impacts of severance tax rate changes on government revenue. Finally, section 8 concludes.

2 Literature

This paper fits into two distinct literatures. First, there is a literature focused on the effects of spatially targeted taxes on investment and economic activity. This literature typically examines spatially varying policies such as state policies, targeted sub-state policies, or regional federal programs, and tests for effects on outcomes such as employment, wages, firm establishment counts, or firm investments. Second, there is a large literature estimating supply elasticities of oil. We review the most relevant examples in both literatures in turn.

2.1 Taxation and Investment

A substantial literature examines the effect of spatially targeted policies, such as taxes, on economic activity. Policymakers face two distinct challenges that include the need to raise sufficient revenues to fund government activities and the desire to design taxes and subsidies to encourage desirable economic activity. However, estimated impacts of tax policy on economic activity are broadly mixed.

The effect of taxation on investment and economic activity is an important topic in the economics literature. In recent years, econometric analyses have found that reduced tax rates can lead to increases in business establishments (Giroud and Rauh, 2017), wages and employment (Ljungqvist and Smolyansky, 2014; Suáez Serrato and Zidar, 2014), and product research and development (Mukherjee et al., 2017), and can attract star scientists (Moretti and Wilson, 2017). Additionally, Rohlin et al. (2014) shows that firms also respond to personal income tax rates.

Conversely, there is mixed evidence on the effectiveness of policies intended to encourage economic activity in particular locations. A number of studies have analyzed "enterprise zones", or programs in which states provide business incentives for firms to locate in economically distressed areas. Ham et al. (2011), Busso et al. (2013), and Freedman (2013) find positive effects of enterprise zones, while Neumark and Kolko (2010) find little effect. Briant et al. (2015) finds heterogeneous effects of an analogous French program, with positive effects only in areas with strong transportation linkages to nearby areas.

One important distinction between our context and other empirical estimates of investment is that investments in oil wells are largely driven by geologic endowments of oil, whereas firm decisions in most sectors are driven by above-ground economic factors. We thus turn to papers which explicitly analyze the determinants of oil supply.

2.2 Oil Supply Elasticities

A large literature estimates supply elasticities for oil, with a wide range of historical estimates. Some of the earliest work estimating elasticities used numerical approaches such as Pindyck (1978). Most historical estimates largely use aggregated data, and results varied widely from about -0.1 to 0.6 (Jones, 1990; Dahl and Duggan, 1996; Kilian, 2009). Some have suggested that the negative price elasticities reflect revenue targeting in noncompetitive world oil markets (Ramcharran, 2002).

Recent research has argued that the key dimension along which oil and gas firms respond to changes in tax rates (and output price) is the choice of drilling a well (Anderson et al., 2018; Newell et al., 2016). This occurs because a large portion of the cost of oil production comes from drilling. Once a well is in place, the marginal cost of production falls close to zero. Anderson et al. (2018) use Texas lease-level data from 1990 to 2007 and find an inelastic drilling response to West Texas Intermediate spot and futures prices. More recent estimates find a drilling elasticity of between 0.7 and just above 1 (Newell et al., 2016; Newell and Prest, 2017). The highest recent estimates are found by Newell and Prest (2017), who focus on unconventional shale wells that may be more elastic due to geological and engineering factors.[2]

While researchers have often assumed that the price and tax elasticities of supply are equal (Metcalf, 2018), some literature does estimate the effects of taxes on supply. Numerical work by Kunce (2003) shows a highly inelastic relationship between oil production and severance taxes, assuming optimal production and exploration over time. More recent papers using detailed analyses of a single state also find that the effect of severance taxes is small, with estimates of the tax elasticity of supply ranging from 0 to 0.3 (Rao, 2015; Reimer et al., 2017).

Our study builds on this literature by utilizing well-level data across multiple states from 1981 to 2015. Motivated by the importance of the drilling decision as shown by Anderson et al. (2018), we focus on the effect of both taxes and oil price on investment in oil extraction wells.

3 Economic Model

3.1 Model Setup

Previous theoretical models of severance tax impacts have emphasized dynamic impacts, including on exploration (Kunce, 2003), the timing of extraction (Deacon, 1993), and the

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[2] Gold (2014) compares drilling wells to factory production because wells are more consistent and replicable than in conventional formations.

size of the deadweight loss (Yücel, 1989). In our model, we focus on the contemporaneous impact of output price and severance taxes that vary across potential drilling sites. The model produces qualitative hypotheses that inform our reduced form empirical analysis.

In order to provide intuition for the empirical relationship between severance tax rates, oil drilling, and government revenue, we develop a model of industry drilling decisions using a 2-location model. A firm in every time period allocates a fixed amount of drilling resources between locations $l = 1$ and $l = 2$. The firm's objective is to maximize profit from drilling by choosing the number of wells to drill in each location. Production from both locations receives an output price, p, so that pre-tax revenue earned per well in location l is pq_l where q_l is the production per well drilled in location l. Anderson et al. (2018) demonstrate that in practice, once a well is drilled, production rates are largely exogenous. Therefore, we focus on the drilling decision and assume that production from a given well in location l is exogenous once the well is drilled.

Next, let w_l be the number of wells drilled in location l. The cost of production per well in location l is $c_l(q_l)$, with $c_l' > 0$ and $c_l'' \geq 0$. Each location charges a severance tax equal to τ_l per barrel of production. Therefore, the firm's after tax revenue per barrel extracted in location l becomes $p - \tau_l$. The firm incurs total drilling costs in location l equal to $d_l(w_l)$, with $d_l' > 0$ and $d_l'' > 0$. The convexity of $d_l(w_l)$ is a result of adjustment costs that occur as drilling in a location increases. For example, as the number of wells drilled increases, capital rental rates go up, pushing up the marginal cost of drilling (Kellogg, 2014). In addition, a high level of drilling activity in one area can require transport of additional labor and capital from long distances, further increasing marginal drilling costs.

In practice, many oil firms produce a drilling budget, to be allocated over a given amount of time. This financial capital available to an oil firm depends on the price of oil, with banks and investors more willing to lend or invest when the oil price is high (Domanski et al., 2015; Azra, 2017). If taxes affect returns to capital, they could also affect the drilling budget available to the firm. Therefore, we assume that the firm has a total drilling budget equal to $B(p, \tau_1, \tau_2)$ with $B_p > 0$ and $B_{\tau_l} < 0$ such that $d_1(w_1) + d_2(w_2) \leq B(p, \tau_1, \tau_2)$. Given this, the firm profit-maximizing decision can be expressed as:

$$\begin{aligned} \max_{w_1, w_2} \sum_{l=1,2} [pq_l - c_l(q_l) - \tau_l q_l] w_l - d_l(w_l) \\ s.t. \\ d_1(w_1) + d_2(w_2) \leq B(p, \tau_1, \tau_2). \end{aligned} \tag{1}$$

3.2 Model solution

To examine the role of price and tax in the model, we assume the firm drills in both locations and spends all of $B(p, \tau_1, \tau_2)$ on drilling. Given these assumptions, the model can be solved through substitution. We use $d_1(w_1) + d_2(w_2) = B(p, \tau_1, \tau_2)$ to solve for $w_2(w_1; p, \tau_1, \tau_2)$ such that given w_1, $w_2(w_1; p, \tau_1, \tau_2)$ provides the maximum number of wells that can be affordably drilled in location 2, conditional on the financial capital available at oil price p and tax rates τ_1 and τ_2. This function represents the drilling budget constraint faced by the extraction firm.

Using this binding drilling budget constraint, the firm's optimization problem can be expressed as a function of just w_1:

$$\begin{aligned} \max_{w_1} \Pi(w_1) = [pq_1 - c_1(q_1) - \tau_1 q_1] w_1 - d_1(w_1) \\ +[pq_2 - c_2(q_2) - \tau_2 q_2] w_2(w_1; p, \tau_1, \tau_2) - d_2(w_2(w_1; p, \tau_1, \tau_2)). \end{aligned} \tag{2}$$

Taking the first-order condition, the interior solution to this optimization problem must satisfy:

$$\begin{aligned}F \equiv \frac{\partial \Pi}{\partial w_1} &= \underbrace{pq_1 - c_1(q_1) - \tau_1 q_1 - d_1'(w_1)}_{\text{Net marginal benefit of drilling in 1}} \\ &+ \underbrace{[pq_2 - c_2(q_2) - \tau_2 q_2 - d_2'(w_2(w_1; p, \tau_1, \tau_2))]\frac{\partial w_2}{\partial w_1}(w_1; p, \tau_1, \tau_2)}_{\text{- Net marginal cost of drilling in 1}} = 0.\end{aligned} \tag{3}$$

The net marginal cost of drilling in location 1 comes from the foregone net marginal benefit of drilling in location 2. Using the implicit function theorem, and as long as $d_l' > 0$, equation 3 can be solved for w_1 that balances the net marginal cost and benefit, producing the solution:

$$w_1^*(p, \tau_1, \tau_2, \phi), \tag{4}$$

where ϕ is a vector of parameters describing the production and investment cost functions in both locations. Using the budget constraint, we can solve for w_2 such that $d_1(w_1^*) + d_2(w_2^*) = B(p, \tau_1, \tau_2)$, yielding:

$$w_2^*(p, \tau_1, \tau_2, \phi). \tag{5}$$

3.3 Effect of Price and Severance Tax on Firm Drilling Behavior

We use the theoretical model to explore the effect of price and tax changes, in dollars per barrel, on the number of wells drilled in location 1.[3] To do this, we apply the implicit function theorem to equation 3 and calculate the derivative of of the equilibrium $w_1^*(p, \tau_1, \tau_2, \phi)$ with respect to price p and tax τ_1 per barrel in state 1. We compare a price increase to an equivalent tax decrease, in dollars per barrel. The effect of an oil price increase on w_1^* can be expressed as:

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[3] This exercise could be repeated for location 2.

$$\frac{\partial w_1^*}{\partial p} = -\frac{\frac{\partial F}{\partial p}}{\frac{\partial F}{\partial w_1^*}} = -\frac{q_1 + q_2 \frac{\partial w_2^*}{\partial w_1^*} - d_2''(.) \frac{\partial w_2^*}{\partial p} \frac{\partial w_2^*}{\partial w_1^*} + (p q_2 - c_2(q_2) - \tau_2 q_2 - d_2'(.)) \frac{\partial^2 w_2^*}{\partial w_1^* \partial p}}{H}, \tag{6}$$

where H is the second derivative of the objective function at the optimum and is less than zero for an interior solution. Therefore, the sign of the price effect depends on the sign of the numerator.

The numerator of Equation 6 suggests the existence of four effects determining the optimal industry response to a change in price. Figure 1, top panel presents each of these effects graphically. The initial equilibrium occurs where the net marginal benefits of drilling are equated across the two locations. A price increase shifts both marginal benefit curves outward (1 and 3 in Figure 1). The first term in equation 6 represents a positive revenue effect that increases drilling in location 1 (2 in Figure 1). When the oil price changes, the opportunity cost of drilling also increases. The second term captures this negative opportunity cost effect, driven by higher marginal benefits of drilling in location 2 (4 in Figure 1). The third term, a first-order budget effect, has a positive effect on drilling because the higher price increases the drilling budget and can increase drilling in both locations (5 and 6 in Figure 1).

Finally, the last term is a second-order budget effect that depends on how a change in price affects the slope of the budget curve. This second-order effect states that drilling increases faster in the location with slower increases in marginal drilling cost. If, for example, $\frac{\partial^2 w_2^*}{\partial w_1^* \partial p} > 0$ (i.e., a negative slope becomes flatter because d_1' increases slower than d_2'), then this effect further increases drilling in location 1.

In summary, the effect of output price on industry drilling is a function of the net effect between the higher revenue in a given location (+), the change in opportunity costs of drilling (−), a first-order budget effect that expands the total number of wells that can be affordably drilled (+), and a second-order budget effect (?). In practice, it is likely that the revenue and budget effects dominate, leading to a positive drilling response to price on average. We test this hypothesis empirically.

Next, we explore the effect of a decrease in tax per barrel of oil in location 1 on the number of wells drilled in location 1. Using equation 3 and the implicit function theorem, this effect is:

$$-\frac{\partial w_1^*}{\partial \tau_1} = \frac{\frac{\partial F}{\partial \tau_1}}{\frac{\partial F}{\partial w_1^*}} = -\frac{q_1 + d_2''(.)\frac{\partial w_2^*}{\partial \tau_1}\frac{\partial w_2^*}{\partial w_1^*} - (pq_2 - c_2(q_2) - \tau_2 q_2 - d_2'(.))\frac{\partial^2 w_2^*}{\partial w_1^* \partial \tau_1}}{H}, \tag{7}$$

with $H < 0$ defined as before. The second panel of Figure 1 walks through the effects of a tax decrease and can be compared to the impact of an equivalent price increase. Specifically, the effect of the decreased severance tax per barrel includes the revenue effect in addition to the first- and second-order budget effects that occur under a price change. However, the impact of a tax decrease does not include the opportunity cost effect (second term in equation 6). While a price increase affects both the marginal benefit and marginal cost of drilling in location 1, a tax decrease in that location only affects the marginal benefit. Therefore, we expect the impact of a change in tax to differ from the impact of a change in price. Empirically, this means that drilling decisions cannot be explained by a single net revenue variable. Without the negative opportunity cost effect, we expect the effect of a tax decrease to be larger in magnitude than an equivalent dollar per barrel increase in price.

Overall, the impacts of price and tax changes depend on several mechanisms influencing firm behavior. Because the mechanisms differ for prices and taxes, we expect that firm responses will not be equivalent.

3.4 Effect of Severance Tax on Government Revenue

We now explore the effect of tax changes in each location on government tax revenue. Often, severance taxes are set as rates charged per dollar of revenue. In this case, $\tau_l = pt_l$, where t_l is the tax charged per dollar of revenue. Given this, government revenue earned in location l, R_l becomes:

$$R_l = t_l * p * q_l * w_l^*(p, pt_1, pt_2, \phi), \tag{8}$$

where we assume a constant price and pt_l has been substituted for τ_l in the solution to the firm drilling problem. Since $q_l * w_l^*(p, pt_1, pt_2, \phi)$ is total production, total revenue is the product of the value of total production and the tax charged per dollar.

Expressing the total differential of R_l provides an estimate for how government revenue changes in response to changes in tax rates in location l:

$$dR_l = \left(p * q_l * w_l^*(p, \tau_1, \tau_2, \phi) + t_l * p^2 * q_l * \frac{\partial w_l}{\partial (pt_l)} \right) dt_l. \tag{9}$$

The response of an increase in tax rate has two effects. It increases government revenue by raising the earnings per barrel produced but decreases revenue because of fewer wells drilled in the location. Which of the two effects dominates depends on the effect of the severance tax per barrel on the number of wells drilled in a location, holding price constant. Therefore, the severance tax elasticity is estimated in the empirical section of this paper and allows us to explore the impact of severance tax changes on government revenue.

4 Econometric Specification and Identification

In order to examine the effect of severance taxes and oil price on drilling decisions, we estimate the parameters of a Poisson count model that includes prices and the severance tax per barrel as explanatory variables, while controlling for unobserved differences in extraction (c_l) and drilling (d_l) costs across space. We assume that the number of wells drilled in reservoir r, state s, and month t is distributed Poisson such that the probability of wells drilled, w_{rst}, in a given location is described by:

$$\Pr(w_{rst} = x) = \exp(-\lambda_{rst}) \frac{\lambda_{rst}^x}{x!}, \tag{10}$$

where λ_{rst} is the expected value of w_{rst}. The expected value of w_{rst} is assumed to take the following form:

$$\mathrm{E}(w_{rst}) = \lambda_{rst} = \exp(\beta_0 + \beta_1 p_t + \beta_2 \tau_{rst} + \beta_3 W_{rt} + \mu_r + \delta_s + f(t)). \tag{11}$$

The average monthly oil price p_t is the expected price to be received over the life of a well and τ_{rst} is the tax per barrel for reservoir r in state s and month t. The coefficients β_1 and β_2 represent the role of the oil price and tax variable in influencing drilling. In the Poisson specification, estimated coefficients describe the proportional effect of a unit increase in an independent variable. Therefore, the effect of variable x on the expected number of wells drilled in a reservoir-state-month is $\frac{\partial \lambda_{rst}}{\partial x} = \beta_x * \lambda$, where β_x is the coefficient on variable x.

Reservoir and state fixed effects, μ_r and δ_s, are included to control for time invariant differences in reservoir characteristics and state policy environments that might effect the profitability of drilling in those locations. For example, some states may offer exemptions to the oil sector.[4] The cumulative resource extraction from reservoir r as of month t is captured by W_{rt}. This controls for the depletion in the nonrenewable resource that potentially affects both production costs, $c_l(q_l)$ and well productivity, q_l. Finally, $f(t)$ is a flexible time control that allows for technological and other changes over time that are common to all reservoirs

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[4] Texas, as an example, offers incentives for enhanced oil recovery methods or recycling of hydraulic fracturing water. See: http://www.rrc.state.tx.us/oil-gas/publications-and-notices/texas-severance-tax-incentives-past-and-present/presenttax/

and states.

In addition to coefficient estimates, we are also interested in the elasticity of the drilling response to prices and severance taxes. Therefore, we calculate elasticities as:

$$e_x = \frac{\partial \lambda_{rst}}{\partial x} * \frac{x}{\lambda_{rst}} = \beta_x * \overline{x}, \tag{12}$$

where $\overline{x}$ is the mean of variable x.

One concern with the assumption of a Poisson distribution is that it imposes equality of mean and variance ('equidispersion') (Cameron and Trivedi, 2010). In fact, the Poisson model still provides a consistent estimate of the parameters of the conditional mean, even when equidispersion fails to hold. In this case, the conventional maximum likelihood standard error estimates are incorrect. To allow for this possibility, we use a generalized version of the White-heteroskedastic consistent standard errors (Cameron and Trivedi, 1998) so that standard error estimates are robust to over- (or under-) dispersion. We also present the results of bootstrapped standard errors in Appendix A. As a solution to this issue, many have proposed the use of the negative binomial regression, which can be more efficient than Poisson (Cameron and Trivedi, 1998). In practice the efficiency gains are often small and the negative binomial model is preferred when predicting probabilities but not for estimating means. Therefore, as a test of model robustness, we present results from negative binomial and other specifications in Appendix B.1.

To control for c_l, d_l, and q_l, we consider reservoirs which cross state boundaries, as in Figure 2, where reservoir r lies in both state s and state s'. Assume that state s's severance tax rate τ_s is higher than state s''s tax rate $\tau_{s'}$. If oil prices go up, then in expectation the number of wells drilled, w, may go up in each region. However, since the net price to producers goes up more in state s', the increase in drilling is larger in state s'. As a result, there are more wells drilled in location $l_{rs'}$ than in l_{rs}. We identify the effect of severance taxes on drilling activity by including individual reservoir effects to control for geological and other unobserved characteristics and focusing on reservoirs which cross state lines. Presumably, geological characteristics and other input and output market structures are similar near the state border, with the main difference being severance taxes.

Our approach relies on the assumption that state boundaries are exogenous with respect to drilling decisions. This is largely justified because state borders are exogenous to the reservoir characteristics underneath, since most state borders were established before widespread development of oil fields. We break this into two components: that the boundary locations are exogenous, and that the severance tax rates are not correlated with other factors which would also interact with oil prices to affect drilling. For the former, we note that it is unlikely that state borders, largely drawn in the 19th century, are correlated with geologic resource endowments because large scale oil extraction did not begin in the U.S. until 1859 (Yergin, 2012). We test the second assumption in Appendix B.2, and provide evidence that suggests that severance taxes are not correlated with broader state regulatory environments or other energy-specific regulations.

Our identification strategy builds on recent research investigating various policies related to the oil and gas sector. For example, Balthrop and Schnier (2016) use a regression discontinuity approach to measure the effect of regulation on the common-pool externality along the Oklahoma and Texas border. They look at drilling and production within five miles on each side of the border. Boslett et al. (2016) use a similar discontinuity approach between the Pennsylvania and New York state border to estimate the effect of New York's moratorium on hydraulic fracturing on housing values in New York. Black et al. (2018) estimate the effect of well impact fees in Pennsylvania on drilling by comparing differences in outcomes with similar areas in neighboring Ohio and West Virginia. More closely related to our paper, Lange and Redlinger (2018) estimate the relationship between drilling and changes in North Dakota regulation by using the border between Montana and North Dakota. They looked at drilling within 20 and 30 miles of the border, which divides several oil and gas reservoirs, and where many wells have been drilled on both sides of the border. They found that new regulations did not have a statistically significant effect on the pace of drilling and production, but did push out some smaller producers. Each of the papers referenced here evaluate either a one-time change in policy, a change in policy in one state, or multiple changes in one state. In contrast, our identification strategy yields a more generalizable result because we are able to exploit the variation in multiple policy (severance tax) changes across states and over time using drilling decisions along state borders over the course of 30 years.

We focus on new well drilling, and not on production in the present analysis. Consistent with the literature (Anderson et al., 2018) and our theoretical model, our dependent variable is the number of wells drilled in a reservoir-state-month. Focusing on drilling is warranted because drilling is relatively easy to adjust, whereas changing production from existing wells is rarely optimal.[5]

5 Data

The data used for this analysis include drilling counts by reservoir-state-month as well as annual data on states' severance tax rates, compiled from official documents describing each state's tax regulations.

5.1 Oil Drilling and Price Data

Our primary dataset is onshore oil wells drilled in 17 states in the contiguous United States from 1981-2015, provided by the oil and gas information firm Drillinginfo.[6] The data include

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[5] An important exception is the new technology of re-fracking, in which companies can hydraulically fracture an existing well multiple times in order to increase production. While re-fracking is rapidly becoming an important tool for operators, less than one percent of horizontal wells were re-fracked during our study period (Nysveen and Wei, 2016).

[6] http://www.drillinginfo.com

the drilling date for each well (spud date), in addition to the reservoir and state where the well was drilled. We calculate the number of oil production wells drilled within 5 and 10 miles of the state border in each reservoir in each month.[7] Thus the unit of observation is the reservoir-state-month. We restrict the sample to reservoirs which overlie precisely two states and exclude wells drilled on public lands. We also drop reservoirs for which the difference in the 10th and 80th percentiles of latitude or longitude are greater than 3 degrees as these likely reflect distinct reservoirs with the same name. Figure 3 shows wells drilled in our study sample.

Table 1 provides summary statistics related to oil drilling and price variables. On average, there are about 0.15 new wells drilled within 5 miles of a state line in each state-reservoir-month, and about 0.3 new wells within 10 miles.[8] The number of observations differs between 5 mile and 10 mile samples because some reservoirs only have wells drilled 5-10 miles from state borders, but not within 5 miles of the border. Therefore, there are some reservoir-states with all-zero observations within 5 miles of the border. These state-reservoirs are dropped when the model is estimated. Monthly oil prices are obtained from FRED.[9] The average real price of oil in our sample is near $50 per barrel (2012 dollars) and the average severance tax is $3.27 per barrel (see below for more details on tax data).

For identification purposes, we focus on wells drilled near state borders. If reservoirs in that sample are systematically different than those which are not, then our results would not extend to the full population of reservoirs. (Put differently, our results would be a biased estimate of any effect on the full population of reservoirs.) We test for selection by using all reservoirs drilled in our sample states in the sample period, and regressing the number

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[7] Wells are typically separated by a minimum of 1000-2500 feet, making smaller distance bands excessively noisy.

[8] This may appear low, but there was very little pad drilling in our sample.

[9] We use WTI price because of endogeneity concerns with using state-level prices, though our results do not depend upon this choice. Spot Crude Oil Price: West Texas Intermediate (WTI) [WTISPLC], retrieved from https://fred.stlouisfed.org/series/WTISPLC, December 1, 2017

of wells drilled in each reservoir in each month on an indicator for whether the reservoir is in our study sample as well as state fixed effects and time controls. We are unable to reject the null hypothesis that study sample reservoirs are different from other reservoirs (that the coefficient on the sample indicator is zero).

One important note about the data structure is that while our raw data are primarily at the well-level, approximately three percent of our observations are at the lease level (a lease describes the area to which an oil company has rights to drill, from a single mineral right owner). A single lease may have multiple wells. In this case, we observe the drilling date of the first well only. We assign this date to all wells in the lease. This implies an assumption that all wells are planned at the same time (which is common) and that they shared a spud date (which is unlikely as wells are typically drilled serially). If we include only the first well drilled and omit subsequent wells drilled when we cannot identify their drilling dates, the results are similar to those presented here.

Also, when creating a panel of reservoir-state-months from well-level data, an assumption must be made about if and when a reservoir enters and exits the choice set of the oil industry. In our primary dataset, we assume that a well enters the choice set on the first date a well is drilled and exits after the last drilled well. This is a conservative dataset because it is likely that a reservoir was known and the industry chose not to drill there for some time. In order to account for this possibility, we construct two alternative datasets. First, we create a balanced panel that assumes that all reservoirs where drilling occurred over the time period of the analysis were in the choice set of the industry over the entire time. Second, we assume that once a reservoir is drilled in, it remains in the dataset (i.e., a reservoir never exits the dataset). Results of our primary specification using the alternative datasets are presented in Appendix B.3.

5.2 State Severance Taxes

Information on state severance taxes was collected individually by state. Table C1 in Appendix C reports the sources for each state. This information was used to construct a panel data set of severance taxes by state from 1981 to 2015. States typically levy one of two types of taxes, a tax per dollar of revenue or a tax per barrel of oil. For states which tax oil production on an ad valorem basis, we multiply the tax rate per dollar times the price of oil to obtain the tax in dollars per barrel. For state-years in which tax rates are in dollars per barrel, we use the statutory rate. We include all taxes on oil production.[10]

Table 2 presents average tax rates by state with the percentage of observations each state is in the sample (column 2). Columns 3 and 4 of the table indicate if a state has a policy expressed in percent of revenue or in dollars per barrel produced. While the most common policy type is a tax on revenue, one third of states charge a tax per barrel. Column 5 indicates the number of policy changes that occur in our dataset. For example, if a state charges a revenue tax only, this provides the count of the changes in this policy rate. If a state charges both a revenue and barrel tax, it counts the number of changes in both of these policies. The majority of states have at least one policy change, with a maximum of nine changes in Wyoming. This policy variation means that our tax per barrel coefficient in equation 11 is identified off variation in price and policy levels over time, as shown in Figure 4. Average tax rates are reported in percent of revenue (column 6) as well as dollars per barrel (column 7).

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[10] Some states levy multiple rates for different purposes (i.e., conservation fee), but appear to be similar to severance taxes. In those instances we used the sum of the rates as the total tax rate. For states with tiered rates, we used the highest as we assume that the relevant rate for new production is the one that applies to the most productive wells.

6 Regression Results

Our primary results are that higher severance taxes are associated with reduced drilling, and that the response of drilling with respect to the severance tax paid per barrel is inelastic. Across specifications, we find that the elasticity of new wells with respect to the price of oil is approximately 0.5 and that the elasticity of new wells with respect to the severance tax per barrel is approximately -0.2 to -0.4. As predicted by the theoretical model, the proportional effect of a change in tax per barrel (-0.08) is larger in absolute value than the effect of an equivalent price change (0.01).

The coefficients on price and tax suggest that a one dollar per barrel increase in price leads to a 1 percent increase in wells drilled, but a one dollar per barrel increase in tax leads to at least an 8 percent decrease in wells drilled. Although it is not the main focus of our results, our estimate of the supply elasticity of drilling with respect to the price of oil ranges between 0.5 and 0.6 in our core specifications. These results are similar to the supply elasticity estimated by Anderson et al. (2018) (0.7), but are smaller compared to Newell and Prest (2017) (1.2/1.6 for conventional/unconventional wells), who focus on drilling decisions between 2010 and 2015.

We organize the discussion of our results as follows: section 6.1 presents our core results. Section 6.2 presents two different tests of the robustness of our results to interstate spillovers. Appendices A and B presents a range of tests of robustness to identification, functional form, and other analytic choices. We also find negligible effects of price and taxes on production and well closure, consistent with the assumption that the key margin along which firms respond to these variables is the number of wells to drill.[11]

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[11] Results of production and closure analyses can be made available upon request.

6.1 Severance Taxes and Drilling

Our primary results are presented in Table 3. The columns describe specifications based on the counts of wells within 5 and 10 miles of each state line. Recalling that the coefficients from a Poisson model are semi-elasticities, the top row shows that a one dollar increase in the price of oil per barrel is associated with a 1.07-1.13 percent increase in the number of wells drilled while a one-dollar increase in the severance tax paid per dollar leads to an 8.13 to 13.3 percent decrease in the number of wells drilled. Consistent with theoretical expectations, the response to price differs from the response to severance taxes. The proportional response to a change in severance tax is larger than a similar change in price, suggesting that the opportunity cost effect associated with a price increase diminishes the incentive for drilling firms to change the location of wells. Also, the budget effect allows an increase in drilling across all locations as a higher oil price means that the industry has access to more capital overall.

The second panel of Table 3 reports the corresponding elasticities, calculated at the sample means as described in equation 12. We see that the oil price elasticity is near 0.5, while the tax elasticity ranges from about -0.3 to -0.4. While the proportional response to a given dollar change in taxes is larger, a proportional change in severance tax per barrel leads to a smaller proportional change than the equivalent proportional change in price. This is because the oil price per barrel is much larger than the tax per barrel. These findings suggest that a 10 percent increase in severance taxes would lead to about a 3 percent decrease in well drilling, making the combined effect about a 7 percent increase in state revenue for every 10 percent increase in tax.[12]

We can reject the hypothesis that the price and tax coefficients are equal in magnitude at a 95 percent confidence level in both specifications. Our results suggest that assuming a common response to price- and tax-driven revenue changes may be misleading (e.g., Rao

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[12] The calculation is $(1 + 0.1) * (1 - 0.1 * 0.266) - 1 \approx 0.07$.

(2015); Metcalf (2018)).

To further illustrate the importance of separately estimating the tax and price effects, we estimate our main specification, including marginal revenue ($p_t - \tau_{rst}$) as the independent variable. Using the 10- (5) mile band, this approach produces a coefficient on marginal revenue equal to 0.25 (0.09), implying a tax elasticity of -0.016 (-0.006). This is an order of magnitude smaller than the tax elasticities calculated from estimates that allow price and tax effects to differ, suggesting that failure to account for the different marginal effects can lead to biased estimates of tax impacts (see Appendix D for a derivation of tax elasticity from the estimated coefficient on marginal revenue). The difference in implied tax elasticity underscores the importance of separately estimating the drilling impact of price and tax rates.

6.2 Spatial Spillovers

Our identification measures the change in drilling on one side of a state line compared to the same reservoir in the other state. If drilling in the other state responds to a tax increase with additional drilling, our base estimates overstate the tax impact. To control for potential spillovers, we take two approaches. In our first approach, we add a measure of the opportunity cost of not drilling elsewhere to our core model. Our identification strategy is designed to estimate the effect of own-state taxes and not to focus on nationwide opportunity costs. As a result, we interpret the estimated opportunity cost with caution. We estimate equation 13, where $\tau_{rs't}$ is a measure of the tax rate charged by the other state, s', for state-reservoir, rs. This other state rate affects the opportunity cost of drilling in state s. We estimate this relationship as:

$$\mathrm{E}(w_{rst}) = \lambda_{rst} = \exp(\beta_0 + \beta_1 p_t + \beta_2 \tau_{rst} + \beta_3 \tau_{rs't} + \beta_4 W_{rt} + \mu_r + \delta_s + f(t)). \qquad (13)$$

In our second approach, we reestimate the core model but restrict the regression sample to either firms which operate in a single state, or firms which operate in multiple states. Multi-state extraction firms may respond to a tax increase by decreasing drilling in the state with the tax change but increasing it elsewhere. If this increase is concentrated in the same reservoir across a state line, this could bias estimated effects away from zero. Single-state firms, though, are less likely to move (physical or financial) capital across state lines because of institutional barriers (e.g., different regulations) created by state borders. Therefore, using only single-state firms should minimize the spillover effects.

Table 4 presents the results of the price and tax coefficients from equation 13, measuring $\tau_{rs't}$ as severance tax per barrel in the adjacent state (columns 1 and 2). While our study is not designed to identify tax spillovers, we find that our core results hold even when controlling for the opportunity cost of not drilling in neighboring states. Price and own-state tax coefficients are not substantially affected by the inclusion of neighboring-state rates.

Columns 3 and 4 of Table 4 demonstrates that our results remain qualitatively similar when excluding multi-state firms, though point estimates suggest smaller responses, consistent with the existence of spillovers from multi-state firms. Of course, the smaller responses could be a result of single-state firms being less responsive to taxes and prices in general. Overall, our elasticity estimates remain robust to controlling for spatial spillovers via the severance tax channel from neighboring states.

7 Policy Simulation

State governments are often reluctant to increase severance tax rates out of concern that drilling activity will drastically decline or go elsewhere. In this section, we use our estimates of the elasticity of drilling with respect to severance taxes (-0.4) to simulate changes in severance tax rates.

To calculate the change in government revenue, we return to the theoretical model and parameterize it using the reduced form elasticity estimate. We approximate equation 9 with discrete changes in the severance tax rates per dollar of revenue (t_l) such that the change in severance tax revenue in state s, (ΔR_s), is given by:

$$\Delta R_s \approx \left(p * q_s * w_s(pt_s, pt_{s'}) \big[1 + e_{pt_s}\big] \Delta t_s \right). \tag{14}$$

e_{pt_s} is the elasticity of drilling with respect to the tax per barrel in state s. We tabulate average wells drilled per month w_s in state s with tax rate t_s and average monthly production per well (q_s) to estimate changes in revenue. Holding constant prices, the initial level of state production, and other states' tax rates, we explore partial equilibrium results of how severance tax revenue changes with changes in severance tax rates.

We examine a scenario where a state considers raising its severance tax rate 1 or 2 percentage points.[13] We use Texas average annual production per well from 2015 (93,256 barrels per well) and the average WTI spot price over the year ($48.79) to calculate the implied severance tax revenue using a base severance tax rate of 4.6 percent. The base number of wells drilled per month is 725. Table 5 shows the results of how the severance tax revenue changes as the tax rate increases. The base case yields severance tax revenue of $152 million. If the severance tax rate were to increase to 5.6 percent, the net increase in revenue from the higher tax rate, holding prices constant, is just over $18.5 million, or 12 percent higher compared to the base case. This estimate is based on moderate changes within the window of observed severance tax rates in the data and is statistically significant at the 95 percent confidence level.[14] Further increasing the rate to 6.6 percent raises revenue by an additional 12 percent from base levels. These results suggest that increasing severance rates from mean levels may lead to increases in government revenue in the short-run.

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[13] The mean severance tax rate over our sample was 6.1 percent.

[14] We do not extrapolate these results to rates outside of the observed severance tax rates.

The policy scenario we put forth is a partial equilibrium calculations. It does not capture how other tax changes may arise in response to severance taxes, where substitution between revenue sources likely occurs. Moreover, we do not capture how oil and gas exploration may change as severance tax changes, which may have important long-term implications (Dahl and Duggan, 1996). Finally, we do not attempt to estimate the effect of drilling decisions on future resource stock sizes. Despite these limitations, our estimates of the drilling elasticity with respect to severance tax in a state are useful for understanding the implications of potential policy changes.

8 Conclusion

The dramatic rise in oil production activity over the past decade has once again highlighted the importance of the sector in some resource-dependent states. With higher levels of production, the debate about the appropriate taxation of oil extraction has reignited. State and local policymakers must balance taxing economic activity to generate government revenue and the potential loss of activity with higher taxation. State governments are often under fiscal pressure and may consider ways to increase tax revenue, particularly given the existence of resource rents associated with the production of nonrenewable resources. However, opponents of higher taxes are often concerned by the potential negative effects on investment and drilling activity. Therefore, an accurate estimate of the tax impacts is crucial.

We theoretically demonstrate that changes in price and taxes affect investment decisions in different ways. Using the theoretical predictions to motivate our empirical model of choice, we look at drilling activity between 1981 and 2015 across 91 reservoirs that cross a state line to estimate how changes in price and severance tax rates per dollar affect drilling. Our results are consistent with theoretical predictions and show that drilling is inelastic with respect to changes in severance taxes. The policy implication is that using state tax rate decreases to incentivize investment may lead to losses of state government revenue. As predicted in the theory, the impact of a change in tax is statistically and economically significantly different than the effect of an equivalent price change.

While our empirical analysis focuses on the U.S. oil industry, our results may have much broader applicability. Our theoretical model describes production siting for tradable goods in a multi-region setting. While our model omits trade costs, the intuition may carry over to settings including international trade as an example. The broader implication of our model is that estimating the relationship between investment and output price net of taxes may yield a different interpretation than if tax effects are estimated alongside price effects.

Limitations of our empirical analysis center around short- versus long-run effects and general equilibrium effects more broadly. We are not able to capture how a single tax change affects drilling activity 20 or 30 years later. Our results are also partial equilibrium in nature. Importantly, we do not analyze how firms' exploration changes with severance taxes, which may have important long-term implications. Finally, while we control for other factors that vary across states, we cannot perfectly observe all differences that could correlate with variation in severance taxes.

Our analysis also raises other research questions. For example, do other parts of the economy respond differently to prices and taxes? Related to severance taxes, what happens if state governments place a portion of severance tax revenues into permanent mineral trust funds? Do these funds help local governments smooth spending over boom and bust cycles? Can these funds be used to help diversify the local economy? How do increases in investment affect tax revenue from other sectors? Each of these are beyond the scope of our current analysis, but may be fruitful areas of future research. Overall, our analysis provides useful policy-relevant information on the responsiveness of the oil production sector to changes in U.S. state level tax rates.

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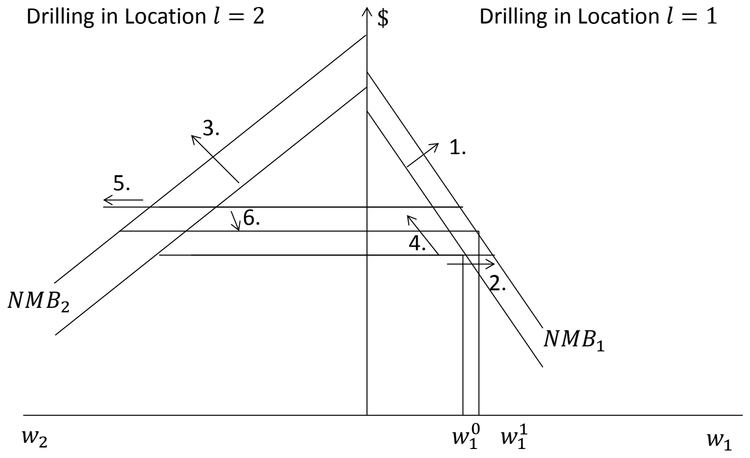
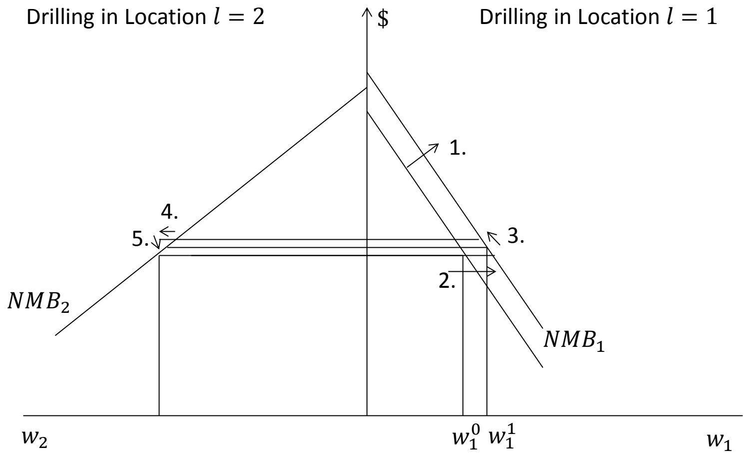
Figure 1: Impact of Price and Tax Change on Drilling

Effect of Price Increase



Note: equilibrium occurs where the marginal benefit of drilling equates across the two locations and the cost of the total number of wells drilled equates to the available budget (represented by the length of the horizontal lines). In the base, this occurs with w_1^0. Price increase increases the net marginal benefit of drilling in location 1 (1). The revenue effect increases drilling in location 1, conditional on the base opportunity cost of drilling (2). The price increase increases the net marginal benefit of drilling in location 2, creating an opportunity cost effect (3). The opportunity cost of drilling in location 1 increases because of the price increase, mitigating the increase in drilling (4). A first-order budget effect increases the number of affordable wells (5), further increasing drilling in location 1 (6). The net impact leads to the new drilling level, w_1^1.

Effect of Tax Decrease



Note: equilibrium occurs where the marginal benefit of drilling equates across the two locations and the cost of the total number of wells drilled equates to the available budget (represented by the length of the horizontal lines). In the base, this occurs with w_1^0 and w_2^0. A tax decrease in location 1 increases the net marginal benefit of drilling in location 1 only (1). The revenue effect increases drilling in location 1 (2) and this raises the net marginal benefit of affordable drilling (3). A first-order budget effect increases the number of affordable wells (4), further increasing drilling in location 1 (5). The net impact leads to the new drilling levels, w_1^1 and w_2^1. The lack of opportunity cost effect leads the change in drilling to be larger than with an equivalent price increase.

Figure 2: Identification Across State Borders

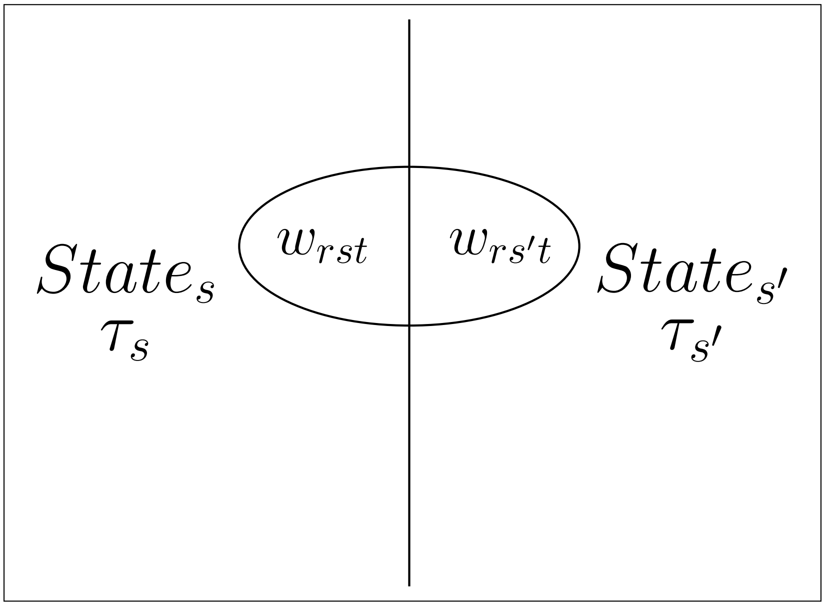
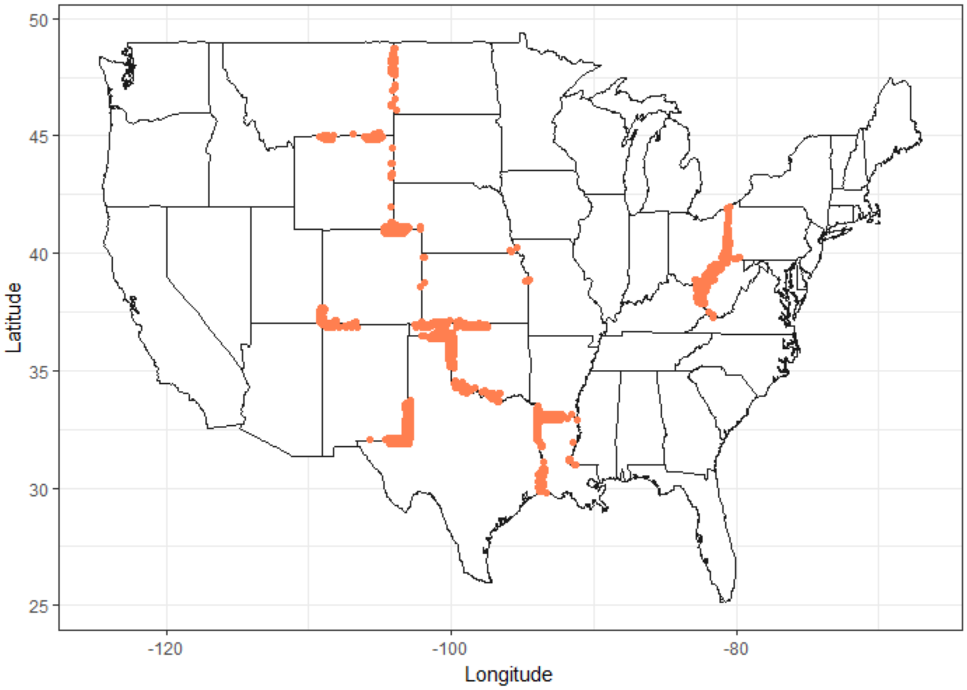


Figure 3: Map of Wells Near State Borders



Dots represent reservoirs within 10 miles of state borders in the contiguous United States.

Figure 4: Severance Tax Rates by State ($ per barrel)

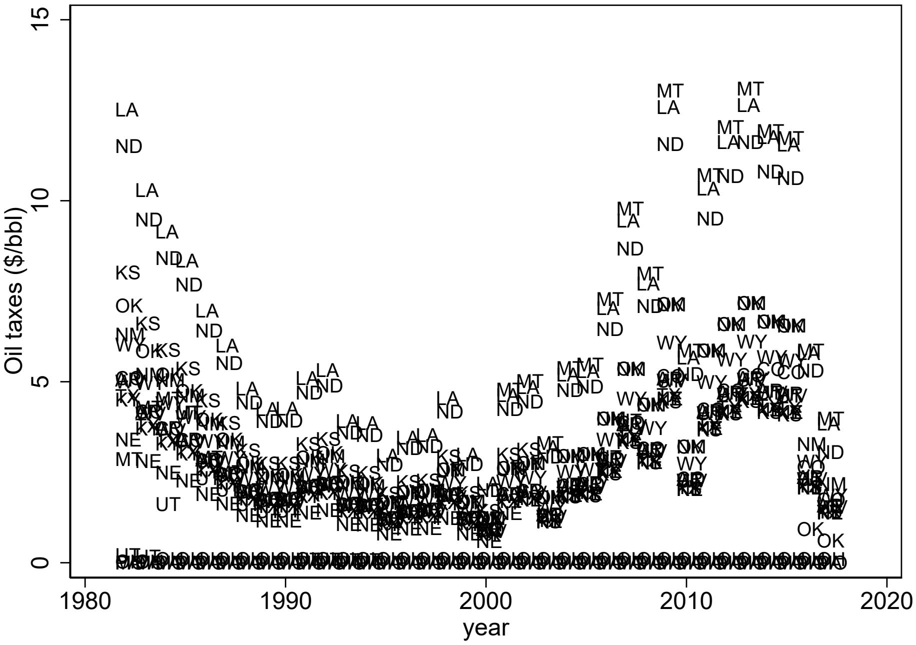


Table 1: Summary Statistics

	Mean	Standard Deviation	Variance	Count
Wells Drilled - 5 miles[1]	0.155	1.639	2.687	39417
Wells Drilled - 5 miles > 0	0.159	1.657	2.745	38577
Wells Drilled - 10 miles	0.298	2.372	5.625	39417
Oil Price ($ per barrel)[2]	50.50	25.38	644.0	39417
Tax Per Barrel ($ per barrel)[3]	3.266	2.345	5.501	39417

Note: The unit of observation is reservoir-state-month.
Sources: [1]Drillinginfo, [2]WTI Spot Crude Oil Price pulled from FRED database, [3]Various state agencies (See Table C1), Authors' calculations.

Table 2: Summary of Severance Taxes

(1) State	(2) Percent of State-Reservoir-Month Observations	(3) Revenue Tax (y/n)	(4) Barrel Tax (y/n)	(5) Number of Policy Changes	(6) Average over Time (%)	(7) Average over Time ($/bbl)
AR	9.4	y	y	3	5.1	2.76
CO	4.3	y	n	0	5.0	2.71
KS	0.3	y	y	8	6.5	3.29
KY	1.6	y	n	1	4.5	2.44
LA	11.7	y	y	1	12.5	6.78
MO	0.2	n	n	0	0.0	0.00
MT	5.0	y	n	7	8.8	5.23
ND	0.8	y	n	1	11.4	6.21
NE	0.7	y	n	4	4.0	2.18
NM	13.2	y	y	2	7.0	3.78
OH	3.1	n	y	1	0.1	0.03
OK	14.6	y	n	1	7.1	3.84
PA	1.5	n	n	0	0.0	0.00
TX	26.1	y	y	2	4.6	2.50
UT	2.3	y	n	7	5.5	2.73
WV	1.6	y	n	0	5.0	2.71
WY	3.6	y	n	9	6.0	3.27

Notes: See Table C1 for sources of information by state.

Table 3: Primary Results

	(1) 5mi	(2) 10mi
Coefficients		
Oil Price	0.0113^{**}	0.0107^{***}
	(0.00550)	(0.00401)
Tax	-0.133^{**}	-0.0813^{**}
	(0.0523)	(0.0381)
Elasticities		
Oil Price	0.571^{**}	0.539^{***}
	(0.278)	(0.202)
Tax	-0.436^{**}	-0.266^{**}
	(0.172)	(0.124)
Different Coefficients?	0.0113	0.0427
N	38577	39417

Notes: Standard errors clustered at the reservoir-state level. +,*,**,*** indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. “Different Coefficients” describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

Table 4: Spatial Spillovers

	(1)	(2)	(3)	(4)
	Adjacent State		Single-State Firm	
	5 mi	10 mi	5 mi	10 mi
Coefficients				
Oil Price	0.0154	0.0189*	0.0128***	0.0126***
	(0.0116)	(0.0103)	(0.00426)	(0.00277)
Tax	-0.191***	-0.131**	-0.0839**	-0.0291
	(0.0712)	(0.0578)	(0.0368)	(0.0335)
Other Tax	0.0101	-0.0809		
	(0.108)	(0.109)		
Elasticities				
Oil Price	0.781	0.952*	0.649***	0.638***
	(0.588)	(0.518)	(0.216)	(0.140)
Tax	-0.627***	-0.428**	-0.275**	-0.0949
	(0.234)	(0.189)	(0.121)	(0.110)
Different Coefficients?	0.00440	0.0222	0.0325	0.602
N	36943	37783	35068	37863

Notes: Standard errors clustered at the reservoir-state level. +,*,**,*** indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

Table 5: Policy Scenario: Raising Severance Tax Rate

Texas Severance Tax Rates (%)	Severance Tax Revenue ($)	Change in Severance Tax Revenue ($)	95% Confidence Interval	Percent Change (%)
4.6	151,741,174			
5.6	170,359,328	18,618,154	[7,514,711, 29,721,598]	12.27
6.6	188,977,482	37,236,308	[15,029,421, 59,443,196]	24.54

A Bootstrapped standard errors

Our results in the main section of the paper consider each well drilled as an independent economic decision. In practice, firms control multiple wells and multiple potential well sites, and may make joint decisions across sites. Unfortunately, we do not observe the controlling firm identity at the time of the drilling decision, so we cannot estimate the joint decision explicitly or cluster at the firm level. In this section, we instead take the approach of bootstrapping our standard errors. Table A1 replicates the estimates of Table 3, but with bootstrapped standard errors with 1000 replications each.

We see that standard errors are similar, and the price and tax results are still significant at standard confidence levels.

Table A1: Primary Results

	(1) 5mi	(2) 10mi
Coefficients		
Oil Price	0.0113**	0.0107***
	(0.00512)	(0.00399)
Tax	-0.133**	-0.0813**
	(0.0436)	(0.0413)
Elasticities		
Oil Price	0.571**	0.539***
	(0.284)	(0.202)
Tax	-0.436**	-0.266**
	(0.197)	(0.135)
Different Coefficients?	0.0301	0.0638
N	38577	39417

Notes: Bootstrapped standard errors with 1000 replications in parentheses. $^{+}$ $p < 0.15$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All specifications include fixed effects for reservoir and state, a quadratic time trend and month of year fixed effects, and controls for cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

B Robustness checks

This appendix presents a variety of robustness tests. First, Section B.1 presents evidence that the core results are robust to a variety of alternative econometric specifications. Then Section B.2 provides evidence that our core results are robust to state regulations beyond severance taxes, including tests of the hypothesis that states with lower severence taxes might have other industry-friendly rules. Finally Section B.3 shows that our results are robust to alternative choice sets.

B.1 Robustness to the the Econometric Specification

This section presents a range of alternative econometric specifications of our core model. Departing slightly from previous table formats, Table B1 shows results for the 5 mile distance bands and Table B2 for the 10 mile distance band for all specifications.

Column (1) presents results using a negative binomial model instead of a Poisson. Summary statistics show that the variance is several times the mean for our outcome variables, while the Poisson model assumes that the variance and mean are equal. While the results in Section 6 do not depend on this assumption (Cameron and Trivedi, 2010), it does suggest considering an estimator that naturally fits over-dispersed data. Results are similar to our core specifications.

In column (2), we use the Brent oil price instead of WTI. While Brent and WTI generally track each other quite closely, the Brent price is considered to be a better measure of world oil prices, whereas the WTI price measures internal US prices. Again, we find that results are similar to our core results.

In Columns (3) and (4), we use quarterly and annual time steps instead of monthly time steps. This may more appropriately reflect the actual firm decision process as drilling decisions are not implemented instantaneously. The results are similar to our core specification,

Table B1: Specification Robustness Specifications, 5 mile band

	(1) Neg Bin	(2) Brent	(3) Quarterly	(4) Yearly	(5) Percent Tax
Coefficients					
Oil Price	0.00929***	0.0115**	0.0116**	0.0127*	0.0119**
	(0.00175)	(0.00570)	(0.00566)	(0.00657)	(0.00540)
Tax	-0.0536***	-0.123**	-0.142**	-0.178**	-0.142***
	(0.0192)	(0.0534)	(0.0569)	(0.0779)	(0.0536)
Percent Tax					8.434
					(13.65)
Elasticities					
Oil Price	0.470***	0.576**	0.585**	0.640*	0.603**
	(0.0885)	(0.286)	(0.287)	(0.332)	(0.273)
Tax	-0.176***	-0.400**	-0.467**	-0.585**	-0.466***
	(0.0630)	(0.173)	(0.187)	(0.256)	(0.176)
Different Coefficients?	0.0130	0.0222	0.0125	0.0227	0.00882
N	38577	38577	12971	3352	38577

Notes: Standard errors clustered at the reservoir-state level. +,*,**,*** indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

but with slightly larger coefficients and elasticities.

Finally, in Column (5) we also control for the severance tax rate as a percentage.[15] While the cofficient on the percent tax is noisy, we see that the coefficients on price and severance tax in dollars per barrel do not qualitatively differ.

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[15] The sample average is 6.5%.

Table B2: Specification Robustness Specifications, 10 mile band

	(1) Neg Bin	(2) Brent	(3) Quarterly	(4) Yearly	(5) Percent Tax
Coefficients					
Oil Price	0.00815***	0.0119***	0.0107***	0.0121**	0.0112***
	(0.00132)	(0.00408)	(0.00409)	(0.00470)	(0.00379)
Tax	-0.0281*	-0.103***	-0.0846**	-0.109**	-0.0886**
	(0.0151)	(0.0361)	(0.0389)	(0.0491)	(0.0363)
Percent Tax					1.533
					(10.97)
Elasticities					
Oil Price	0.412***	0.594***	0.540***	0.610**	0.565***
	(0.0669)	(0.204)	(0.207)	(0.237)	(0.192)
Tax	-0.0918*	-0.333***	-0.276**	-0.357**	-0.289**
	(0.0494)	(0.117)	(0.127)	(0.160)	(0.119)
Different Coefficients?	0.157	0.0579	0.0382	0.0322	0.0172
N	39417	39417	13256	3430	39417

Notes: Standard errors clustered at the reservoir-state level. +,*,**,*** indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

B.2 Tests of Robustness to State Regulatory Endogeneity

It is possible that other state characteristics confound estimation of the effect of severance taxes.[16] If these characteristics are correlated with severance taxes, then our estimation of the effect of severance taxes could be the result of changes in these other factors. In this section, we proxy for a state's regulatory environment by controlling for state level voting and by including state corporate tax rates as additional controls.

First, we control for the average League of Conservation Voters score of each state's Sen-

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[16] For example, states might choose to process well drilling permits quickly or slowly, or they might have permissive or difficult unitization rules. When multiple individuals have claims to the same pool of oil, "unitization" allows them to coordinate and avoid the tragedy of the commons.

ate delegation (see columns 1 and 2 of Table B3). We choose Senate delegation in order to represent statewide preferences, as in Ferraro et al. (2007). Then, we control for the share of the state legislature which is Republican (Columns 3 and 4 of Table B3).[17] The intuition is that high LCV scores or lower percent Republican can serve as proxy variables for the electorate's support for non-tax regulations. Finally, we also control for state corporate taxes, which reduce income from drilling and may be correlated with severance taxes (Columns 5 and 6 of Table B3). Table B3 demonstrates that when controlling for a state's policy environment, our estimated impacts remain qualitatively similar. Severance tax elasticities remain between -0.3 and -0.62.

Table B3: Robustness to State Regulatory Climate

	(1)	(2)	(3)	(4)	(5)	(6)
	LCV Score		Legislature Share		Corp Tax	
	5 mi	10 mi	5 mi	10 mi	5 mi	10 mi
Coefficients						
Oil Price	0.00985	0.0110**	0.00920*	0.00901**	0.0158***	0.0136***
	(0.00727)	(0.00529)	(0.00514)	(0.00396)	(0.00573)	(0.00448)
Tax	-0.132**	-0.0832**	-0.110**	-0.0607^{+}	-0.188***	-0.118***
	(0.0513)	(0.0365)	(0.0446)	(0.0382)	(0.0456)	(0.0375)
Elasticities						
Oil Price	0.498	0.555**	0.466*	0.455**	0.797***	0.686***
	(0.368)	(0.267)	(0.260)	(0.200)	(0.290)	(0.226)
Tax	-0.434**	-0.272**	-0.361**	-0.198^{+}	-0.617***	-0.387***
	(0.168)	(0.119)	(0.147)	(0.125)	(0.150)	(0.123)
Different Coefficients?	0.00943	0.0297	0.0132	0.138	0.0000279	0.00192
N	38577	39417	38240	39080	38577	39417

Notes: Standard errors clustered at the reservoir-state level. $^{+,*,**,***}$ indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

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[17] Results are similar with an indicator for whether the Governor is Republican. This analysis omits Nebraska, which has a non-partisan legislature.

B.3 Alternative Assumptions about the Choice Set

This section presents our primary model results under alternative assumptions about industry choice sets. In our base specification, we assume that a reservoir enters the industry choice set upon first being drilled and exits after the last time it was drilled. Tables B4 presents results under alternative assumptions about the choice set. Columns 1 and 2 assume that once drilled, reservoirs never leave the choice set. Columns 3 and 4 assume that all observed reservoirs are in the choice set for the entire period of study. Results are robust to these alternative choice set assumptions.

Table B4: Primary Results with Alternative Choice Sets

	(1)	(2)	(3)	(4)
	No Exit		Balanced Panel	
	5 mi	10 mi	(3)	(4)
Coefficients				
Oil Price	0.0146***	0.0140***	0.0140***	0.0135***
	(0.00473)	(0.00472)	(0.00483)	(0.00350)
Tax	-0.143***	-0.0873***	-0.146***	-0.0908***
	(0.0420)	(0.0315)	(0.0432)	(0.0326)
Elasticities				
Oil Price	0.783***	0.748***	0.754***	0.727***
	(0.252)	(0.183)	(0.261)	(0.189)
Tax	-0.498***	-0.304***	-0.513***	-0.319***
	(0.147)	(0.110)	(0.152)	(0.115)
Different Coefficients?	0.000938	0.0114	0.000906	0.00992
N	72643	75254	77743	80494

Notes: Standard errors clustered at the reservoir-state level. +,*,**,*** indicate statistical significance at the 15%, 10%, 5%, and 1% level, respectively. All specifications include a quadratic time trend; month, state, and reservoir fixed effects; and cumulative drilling. "Different Coefficients" describes the p-value for testing the null hypothesis that the coefficients for oil price and tax are equal in magnitude.

C Source Information for State Severance Taxes

In this appendix we report the source for each state's severance tax information. Data from each source were compiled into a state-year severance tax database including all taxes charged on the production of oil. The primary source of state-level tax rates is The Book of States. In some cases where noted, the information was incomplete and required additional searching among state agencies. We provide the URLs to the sources in the table.

Table C1: Sources for State Severance Tax Information

State	Source
Alabama	Book of the States[1]
Arkansas	https://www.dfa.arkansas.gov/excise-tax/miscellaneous-tax
Colorado	https://www.colorado.gov/pacific/tax/severance-tax-instructions-and-forms[2]
Kansas	https://www.ksrevenue.org/taxrates.html[3]
Kentucky	Book of the States
Louisiana	http://www.dnr.louisiana.gov/assets/TAD/data/severance/la_severance_tax_rates.pdf
Missouri	Book of the States[4]
Montana	https://mtrevenue.gov/taxes/natural-resource-taxes/oil-and-natural-gas-production-tax/
Nebraska	Book of the States
New Mexico	https://law.justia.com/codes/new-mexico/[5]
North Dakota	Book of the States
Ohio	Book of the States
Oklahoma	Book of the States
Pennsylvania	Book of the States[4]
Texas	Book of the States
Utah	Book of the States
West Virginia	Book of the States
Wyoming	http://revenue.wyo.gov/mineral-tax-division

Notes: [1]Severance tax rates are listed in chapters called Finance(s) or State Finance(s) at: http://knowledgecenter.csg.org/kc/category/content-type/content-type/book-states. [2]BOS includes Colorado, but only reports the conservation tax; severance tax rates came from this source. [3]BOS includes Kansas, but earlier reports do not have the tax, so severance tax rates came from this source. [4]No entry in the BOS indicating the state does not have a severance tax. [5]Chapter 7, Articles 29-32, Section 4.

D Tax Elastictity from Marginal Revenue

In this appendix, we illustrate the impact of estimating tax elasticities without allowing price and tax effects to differ. Define marginal revenue as $MR = p - \tau$, where p is the output price of oil and τ is the tax paid per barrel. If output is $y = y(MR(p,\tau))$, the tax elasticity can be expressed as:

$$\frac{\partial y}{\partial \tau}\frac{\tau}{y} = \frac{\partial y}{\partial MR}\frac{\partial MR}{\partial \tau}\frac{\tau}{y}. \tag{15}$$

Since we know that $\frac{\partial MR}{\partial \tau} = -1$, equation 15 is equivalent to:

$$-\frac{\partial y}{\partial MR}\frac{\tau}{y}. \tag{16}$$

Now define the empirically estimated elasticity based on the inclusion of MR as the independent variable influencing drilling decisions as:

$$\hat{e} = \frac{\partial y}{\partial MR}\frac{MR}{y}. \tag{17}$$

Multiplying equation 16 by $\frac{p-\tau}{p-\tau}$ produces:

$$\frac{\partial y}{\partial \tau}\frac{\tau}{y} = -\frac{\partial y}{\partial MR}\frac{p-\tau}{y}\frac{\tau}{p-\tau} \tag{18}$$

$$= \hat{e}\left(\frac{\tau}{p-\tau}\right). \tag{19}$$

Recalling that τ, the tax charged per barrel, can be expressed as $\tau = p * t$ where t is the tax rate per dollar of revenue, equation 19 simplifies to:

$$= \hat{e}\left(\frac{t}{1-t}\right) \tag{20}$$

This result suggests that as long as the tax rate per dollar is greater (less) than 0.05, the estimated marginal revenue elasticity is smaller (larger) in absolute value than the tax elasticity, also in absolute value. This follows from equation 20 which includes the estimated marginal revenue elasticity scaled by $\frac{t}{1-t}$. The term is bigger than 1 if $t > 0.5$.

To illustrate the numerical impact of assuming a single coefficient on marginal revenue, we estimate our core model with only marginal revenue as a dependent variable. This specification imposes that $\beta_1 = \beta_2$ from equation 11. Our coefficient estimate for the 10-mile band is 0.25 (s.e. $= 0.117$), and is statistically significant at the 5% level. Using this estimate with an average tax rate per dollar of 0.06 in equation 20 produces:

$$\frac{\partial y}{\partial \tau}\frac{\tau}{y} = -0.25 * \left(\frac{0.06}{1-0.06}\right) = -0.016. \tag{21}$$

Comparing this estimate with the equivalent 10-mile estimated elasticity of -0.266 in our model that allows price and tax effects to differ demonstrates that failing to allow for differential effects can lead to meaningful differences in estimated tax elasticities. Using the 5-mile MR estimate produces a statistically insignificant estimated elasticity of -0.006, compared to a statistically significant -0.436, again underscoring the difference when imposing that the marginal effect of price and tax is equivalent.