Patchwork Policies, Spillovers, and the Search for Oil and Gas

By Eric Lewis*

The United States has a complex patchwork of mineral ownership, where rights to oil and gas may be owned by the federal government, state governments, or private agents. I show why the policies imposed by one owner have theoretically ambiguous spillover effects on the drilling and production outcomes of neighboring plots of land. Exploiting a natural experiment in Wyoming with exogenous ownership assignment, I find significant spillovers: federal land close to state land has a lower probability of drilling than federal land far from state land.
JEL: Q35, Q38, Q58

The United States has a decentralized system of mineral ownership, where the rights to extract underground mineral resources may be owned by the federal government, state governments, or private parties. In contrast, most other nations have a centralized system with all mineral rights owned and managed by one government body, regardless of surface ownership. I discuss the effects of this complex patchwork of mineral ownership, exploring how the identity and policies of owners have spillover effects on the oil and gas extraction outcomes of nearby land.[1]

Different owners impose very different policies on oil and gas firms. The U.S. federal government, which manages oil and gas leasing on US federal land, tends to have stricter environmental protection requirements and longer delays in processing paperwork (SWCA Environmental Consultants, 2012; Snow, 2013). In contrast, state governments, which regulate drilling on both state and private land, have a reputation for imposing smaller costs on firms. These policy differences may lead to large differences in oil and gas outcomes between federal, state, and private land, and there is currently a major policy debate over the benefits and costs of federal, state, and private ownership.[2]

But in addition to direct effects, policies may also have spillover effects on

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[1] Throughout this discussion, any references to ownership refer to subsurface or mineral ownership unless otherwise specified.

[2] See, for example, Loris (2013).

the drilling and production outcomes of nearby land. Such spillovers are likely to be economically significant given the widespread patchwork nature of mineral ownership in the United States. For example, much of the western United States consists of federal land bordering state and private land.[3] Accounting for such spillovers is important in designing and evaluating policies. For example, if drilling rates on federal land are low, this may be due either to federal policies, spillovers from nearby state and private land, or both.

I show why spillovers can result from how firms search for oil and gas. Firms typically consider multiple potential drilling sites. Each well drilled informs the firm about the expected profitability of drilling on the remaining sites. A firm's choice set of drilling sites may span federal, state, and private land.[4] Because the firm considers policies for each plot of land in determining its drilling strategy, policies on one plot of land can affect the probability of drilling on other plots of land.

Spillovers are theoretically ambiguous because of two contrasting effects: the substitution effect and the total expected cost effect. The substitution effect results from the firm preferring to begin its search for oil and gas on a low-cost plot, all else equal. Proximity to a low-cost plot leads to a lower probability of drilling and production for a high-cost plot. The total expected cost effect comes because proximity to a low-cost plot lowers the total expected costs of drilling operations, which increases the probability of drilling and production for a high-cost plot. Which effect dominates is an empirical question.

To measure spillover effects, I exploit a natural experiment where mineral ownership was exogenously assigned. The US federal government transferred about one-eighteenth of federal land in Wyoming to the State of Wyoming. The plots that were transferred were regularly spaced "islands" within a larger "sea" of federal land (Figure 1). In much of southwest Wyoming, this pattern has remained fairly persistent (see Figure 2). As a result, there is exogenous variation in whether land is state land, federal land close to state land, or federal land far from state land. I identify spillovers by comparing drilling and production outcomes on federal land that is close to state land with that of federal land that is far from state land.

Using an intent-to-treat specification, I find evidence of both the substitution and the total expected cost effects. Evidence of the substitution effect is seen in drilling probabilities: Federal land furthest from state land is 13% more likely to have drilling than federal land adjacent to state land. Evidence of the total expected cost effect is seen in well production: Average well production for wells furthest from state land are 20% higher than those of wells on sections that are adjacent to state land. This suggests proximity to state land led to drilling of federal sites with lower

[3]The U.S. federal government owns 31% of mineral rights and 28% of surface rights in the United States. Of the 700 million acres in US federal ownership, 422 million acres in Western states (U.S. Department of the Interior, Bureau of Land Management, 2012). This is a region where the Land Ordinance of 1785 transferred significant acreage of isolated plots of land to state governments. Within these western states, there is also significant federal acreage that is close to private mineral lands due to transfers of federal lands to homesteaders and railroad companies.

[4]Evidence of this is seen in the patchwork ownership of oil and gas fields. Using Energy Information Administration data on a sample of oil and gas fields in the Western United States, I find that 68% of oil and gas fields are partially but not completely in federal ownership.

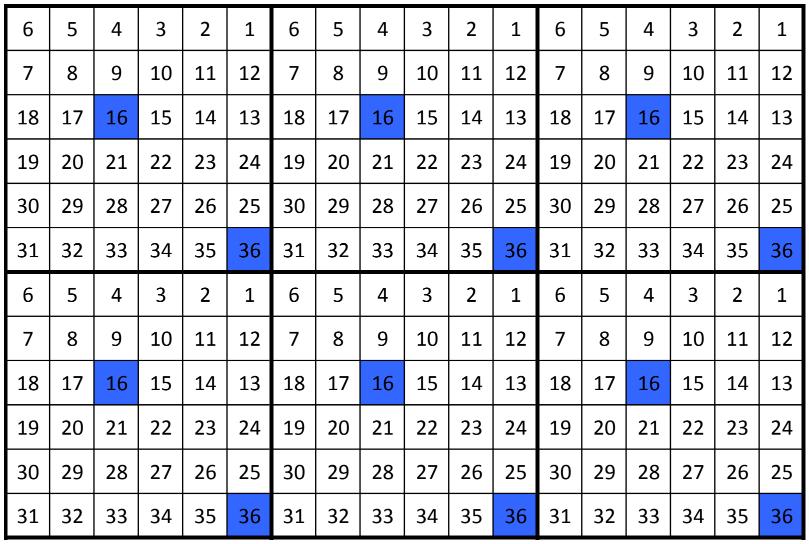

FIGURE 1. DIAGRAM SHOWING ORIGINAL SECTION NUMBERING. THE 16TH AND 36TH SECTIONS, SHOWN IN BLUE, WERE TYPICALLY ASSIGNED TO STATE OWNERSHIP.

expected productivity.

I find some suggestive evidence that these differences in drilling and production were at least partially driven by federal federal environmental protection measures introduced in the 1970s, as the large difference in drilling probabilities only emerges in the 1980's. I also find that the effects of these policies have the largest effect in places with lower but positive geological productivity, while direct and spillover effects of policies had little impact on production in places with highest geological productivity.

This paper builds on two strands of literature. First, a number of papers show how firms learn from previous drilling and production as they search for oil and gas, including Hendricks and Kovenock (1989); Hendricks, Porter and Tan (1993); Lin (2013); Levitt (2016); Covert (2015). This paper is the first to show how the spatial distribution of mineral ownership and policy interacts with this learning process. A second strand of literature uses geographic variation in ownership and policies to show that such ownership and policies can have large effects on oil and gas industry outcomes, including bids for oil and gas leases, drilling, and production (Fitzgerald, 2010; Balthrop and Schnier, 2016; Fitzgerald and Stocking, 2014; Vissing, 2016; Edwards, O'Grady and Jenkins, 2016).[5] This paper is the first to demonstrate that owners'policies may also have spillover effects.

[5]Another related paper is Kunce, Gerking and Morgan (2002), which use the same natural experiment as Edwards, O'Grady and Jenkins (2016), but was later retracted (Gerking and Morgan, 2007).

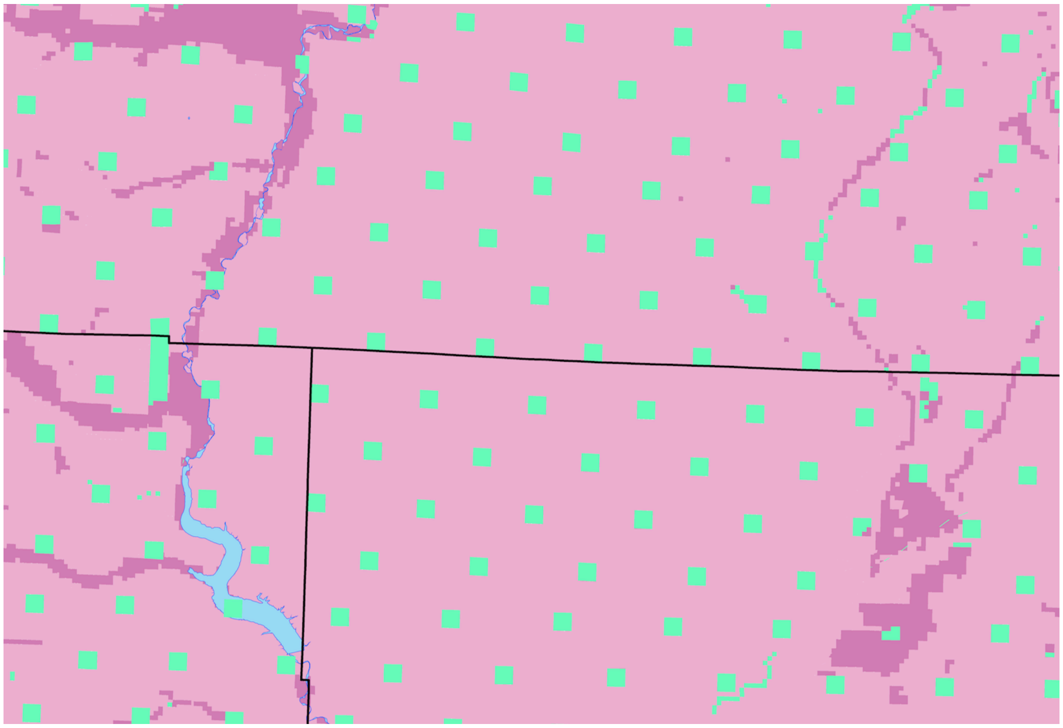

FIGURE 2. CURRENT MINERAL OWNERSHIP IN A SUBSET OF THE GREATER GREEN RIVER BASIN. DARK PINK DENOTES PRIVATE OWNERSHIP, LIGHT PINK DENOTES FEDERAL OWNERSHIP, AND LIGHT GREEN DENOTES STATE OWNERSHIP. BLUE INDICATES WATER, WHERE MINERAL RIGHTS ARE OWNED BY THE STATE. THE DARK LINES ARE COUNTY LINES.

The paper proceeds as follows: In the next section I discuss background on federal and state oil and gas policies. In section II, I write a simple model to show why policies have ambiguous spillover effects on nearby land. In section III, I describe the natural experiment, the data, and identification. Section IV contains the empirical analysis, and section V concludes.

I. Institutional Background

The US federal government and state governments manage oil and gas leasing, environmental reviews, permit granting, and royalty collection on their respective mineral lands. State governments also manage permitting and environmental reviews for privately-owned land. Federal and state oil and gas regulations are very complicated, and vary in a variety of dimensions (Krupnick, Gottlieb and Kopp, 2014), some of which I discuss below:

Environmental protection: Both federal and state governments impose environmental protection requirements for drilling. On federal land, environmental protection is largely a result of the National Environmental Protection Act of 1970

(NEPA). Because of NEPA, the Bureau of Land Management assesses what environmental protection requirements a firm must meet in order to drill and produce oil and gas on a federal lease (Pendery, 2010). These requirements, known as stipulations, are published prior to leases being auctioned off to oil and gas firms. State governments typically also impose environmental stipulations which are also published prior to the state auctioning off state oil and gas leases.

At least in Wyoming, a textual comparison of federal and state stipulations shows that federal stipulations tend to be stricter. Examining stipulations from 2008 and 2009, I find that federal but not state stipulations include protections for nesting raptors and endangered and vulnerable species like the blowout penstemon and the mountain plover. Federal land restricts operations within 500 feet of riparian areas, whereas state stipulations only restricts operations within 300 feet. While both federal and state stipulations restrict operations to protect the greater sage grouse, the restricted date range is weakly longer on federal land.[6] This squares with anecdotal evidence from conversations with industry participants that federal environmental protection requirements are stricter.

Royalties: The royalty rate for production from wells on Wyoming state land is 15% while the royalty rate for production from wells on federal land is 12.5%.

Primary terms: Oil and gas leases typically have a primary term during which time the firm can drill. If the firm drills a productive well during the primary term, the firm retains the lease until production ends. Otherwise the lease expires when the primary term ends. Federal leases have a primary term of 10 years whereas Wyoming state lease terms are 5 years.

Delays: Federal and state land may differ in paperwork processing delays, including delays in making leases available as well as delays in processing drilling approvals for firms that have acquired leases. Anecdotally, delays are more common on federal land (Snow, 2014),[7] and Edwards, O'Grady and Jenkins (2016) finds evidence of longer delays on federal land relative to Wyoming state land.

Other differences: In auctioning off leases, reserve prices are $1 per acre for Wyoming state leases and $2 per acre for federal leases. After the lease begins but prior to production, the lessee must pay an annual rental fee equal to $1 per acre for Wyoming state leases and $2 per acre for federal leases. Federal and state policies may also differ in ways that are difficult to quantify and compare, such as support services for lessees and the degree to which stipulations are enforced.

[6] In other dimensions federal and state of Wyoming stipulations are similar. Both have the same operation date restrictions to protect the winter habitat of big game, and both have similar restrictions on how close to historic trails firms can operate. I found no examples where state stipulations were stricter than federal stipulations.

[7] For example, (Snow, 2014) cites one industry representative who testified that "BLM has piled more paperwork onto an overburdened staff who cannot process leases, environmental analyses, or permits in a reasonable timeframe."

II. Modeling Search and Spillovers

I discuss a simple model of policy spillovers where I abstract away from institutional complexity and assume that federal and state policies differ only in the fixed costs (e.g., the environmental compliance costs) they impose on firms. While simple, this model demonstrates why spillover effects are theoretically ambiguous. The model is a search and learning model similar to those of Hendricks and Kovenock (1989); Hendricks, Porter and Tan (1993); Lin (2013); Covert (2015); Levitt (2016), where a firm solves an optimal learning and stopping problem, learning from past drilling to decide whether it should drill an additional well. All proofs are in the online appendix.

After discussing the main model, I briefly discuss a number of extensions to examine the spillover effects of other policies, including delays, primary terms, and delays. I also briefly discuss how the model changes with multiple firms and common pools. A more detailed discussion of these extensions, along with proofs, is in the online appendix.

A. *A Model With Fixed Cost Differences*

Model Preliminaries. — There is a single firm that is searching for oil. It has two adjoining plots, plot 1 and plot 2, and each plot can have at most one well drilled. The firm pays a cost C_F to extract oil if the plot is in federal ownership and C_S to extract oil if the plot is in state ownerships. As federal land is anecdotally costlier to operate on, I impose (without loss of generality) that $C_F > C_S$. These costs are the sum of the costs of complying with environmental stipulations and the costs of drilling.

To examine spillover effects, I examine how proximity to state land affects drilling and production outcomes on federal land. To do this, I compare a case where both plot 1 and plot 2 are in federal ownership ($C_1 = C_2 = C_F$) with a case where plot 1 is in state ownership and plot 2 is in federal ownership ($C_1 = C_S, C_2 = C_F$). The spillover effect of state land is identified by how outcomes on plot 2 differ between the federal-federal case and the state-federal case.

The firm has initial signals μ_1 and μ_2 of the expected productivity of plots 1 and 2 respectively. The signals μ_1 and μ_2 are drawn from a cumulative distribution function $G(\mu_1, \mu_2)$. Conditional on μ_1 and μ_2, there is a cumulative distribution function of oil reserves $F(R_1, R_2|\mu_1, \mu_2)$, with $E(R_1, R_2|\mu_1, \mu_2) = (\mu_1, \mu_2)$. As there are no systematic geological differences between the two plots, G and F are symmetric about the 45 degree line: $G(\mu_i, \mu_j) = G(\mu_j, \mu_i)$ and $F(R_i, R_j|\mu_i, \mu_j) = F(R_j, R_i|\mu_j, \mu_i)$ for all values of μ_i, μ_j, R_i, and R_j. Actual realized oil reserves are r_1 and r_2. When the firm drills on plot 1, it learns r_1 and then updates its beliefs about the distribution of R_2.

Oil prices are normalized to 1 and there are no other costs or taxes. Oil reserves are extracted immediately.[8] Therefore profits for drilling plot i are $r_i - C_i$. The firm discounts the future with a discount factor $\delta < 1$.

The firm has three options. The first option is to initiate drilling on plot 1, learn r_1, update its beliefs about R_2, and decide whether to drill plot 2. This gives expected profits

$$\pi_1(\mu_1, \mu_2, C_1, C_2) = \mu_1 - C_1 + \delta E_{R_1|\mu_1,\mu_2}[\max\{E_{R_2|r_1,\mu_1,\mu_2}(R_2) - C_2, 0\}]. \tag{1}$$

Alternatively, it may initiate drilling on plot 2, learn r_2, update its beliefs about R_1, and decide whether to drill plot 1. This gives expected profits

$$\pi_2(\mu_1, \mu_2, C_1, C_2) = \mu_2 - C_2 + \delta E_{R_2|\mu_1,\mu_2}[\max\{E_{R_1|r_2,\mu_1,\mu_2}(R_1) - C_1, 0\}]. \tag{2}$$

Or it may choose no drilling, with expected profits $\pi_0 = 0$.[9]

Model Solution. — Figure 3 plots the optimal choice of the firm as a function of μ_1 and μ_2 for both the federal-federal case ($C_1 = C_2 = C_F$) and the state-federal case ($C_1 = C_S$ and $C_2 = C_F$). In the federal-federal case, the firm drills plot 1 first if the signals are in region J; it drills plot 2 first if the signals are in region A or E; and it does not drill at all if the signals are in region D, E, or H. In the state-federal case, the firm drills plot 1 first if the signals are in regions B, H, or J; it drills plot 2 first if the signal are in regions A or D; and it does not drill at all if signals are in region E. Indifference curves for the federal-federal and the state-federal cases are drawn in solid and dashed lines, respectively.

In comparing the federal-federal case with the state-federal case, the two sets of indifference curves in Figure 3 illustrate how proximity to state land has theoretically ambiguous effects on the probability that federal land is the sight of the exploratory well. On one hand, shifting from the federal-federal case to the state-federal case shifts the $\pi_1 = \pi_2$ to the left, which decreases the likelihood that plot 2 will be drilled first by the region B. This implies that federal land will be less likely to be the site of an initial exploratory well if it is close to state land. I call this the substitution effect. On the other hand, shifting from the federal-federal case to the state-federal case shifts the $\pi_1 = 0$ and $\pi_2 = 0$ indifference curves toward the origin. This increases the probability that plot 2 will be drilled first by the region D. This implies that federal land will be more likely to be the site of an exploratory well if it is close to state land. I call this the total expected cost effect.

Which effect dominates is theoretically ambiguous and depends on the distribution $G(\mu_1, \mu_2)$, which affects whether the integral over the region B is larger

[8]More generally, r_1 and r_2 can be thought of as the present discounted value of reserves at the time the well is drilled.

[9]I ignore without loss of generality a fourth possibility—that the firm will choose to drill both plots simultaneously. This is because in the search for conventional oil and gas reservoirs, the costs of drilling is high, the probability of drilling a productive well is low, and reserves tend to be correlated (McKie, 1960). Therefore the value of drilling sequentially is high, and it is rare that two exploratory wells in close proximity are drilled simultaneously.

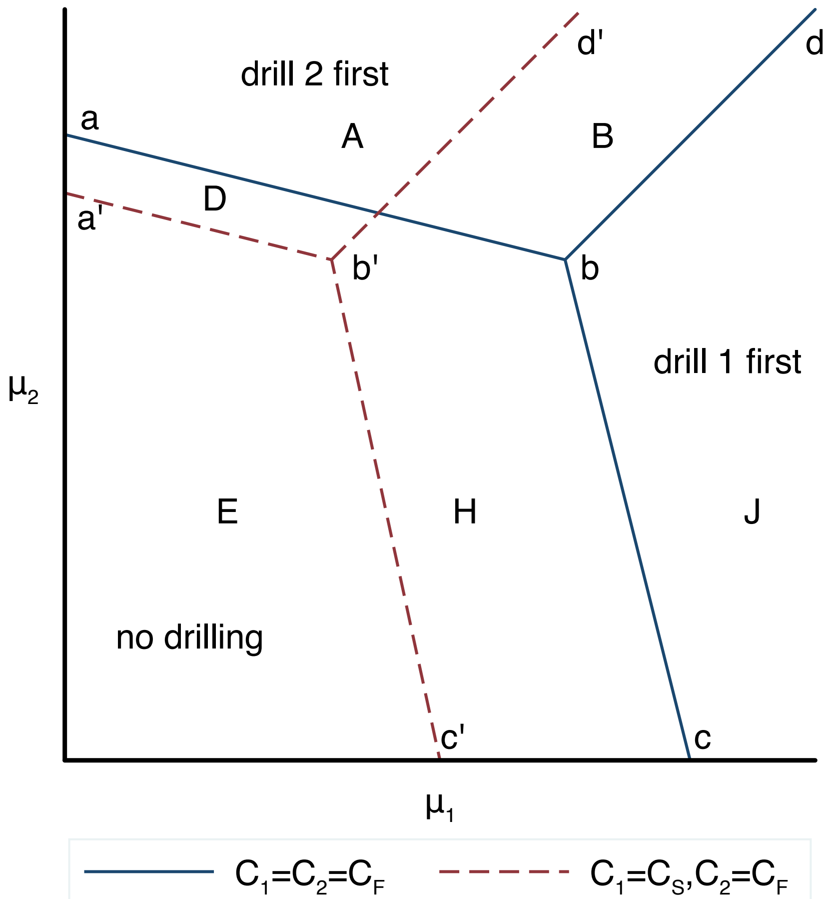

Figure 3. Diagram of optimal first-period drilling location choice as a function of expected production μ_1 and μ_2 under two different cost regimes. The first regime is $C_1 = C_2 = C_F$ and is denoted with the solid lines. The second is $C_1 = C_S$ and $C_2 = C_F$, and is denoted with the dashed line. The solid line $\overline{ab}$ and dashed line $\overline{a'b'}$ designate where $\pi_2 = 0$ (and $\pi_1 < 0$). The solid line $\overline{bc}$ and dashed line $\overline{b'c'}$ designate where $\pi_1 = 0$ (and $\pi_2 < 0$). The solid line $\overline{bd}$ and dashed line $\overline{b'd'}$ designate where $\pi_1 = \pi_2$ (and $\pi_1 > 0$).

than that over the region D. For example, if signals are strongly correlated, then the mass of signals in D is small, and the substitution effect dominates. If a large fraction of signals are marginal and signals are not too strongly correlated, then the mass of signals in D is big and the total expected cost effect dominates. It also depends on the distribution F—how informative production on one plot is of the productivity of the other plot—which determines the positions of the indifference curves $\pi_1 = 0$, $\pi_2 = 0$, and $\pi_1 = \pi_2$.

Proximity to state land also has theoretically ambiguous effects on other outcomes of interest:

Probability of ever drilling: Proximity to state land may either increase or decrease the likelihood that federal plot 2 ever has drilling. On one hand, proximity to state land decreases the likelihood that plot 2 is the site of an initial well (the substitution effect), and because not all exploratory drilling lead to follow-up drilling, proximity to state land reduces the likelihood that plot 2 is ever drilled. On the other hand, proximity to state land shifts the $\pi_1 = 0$ and $\pi_2 = 0$ indifference curves inward (total expected cost effect) which increases the probability that plot 2 is ever drilled. This happens both through increasing the likelihood that plot 2 is drilled first (the shift in the $\pi_2 = 0$ indifference curve), as well as through increasing the likelihood that plot 1 is drilled first (the shift in the $\pi_1 = 0$ indifference curve), which sometimes leads to a follow-up well on plot 2.

Plot-level production: Production can only happen if a well is drilled; otherwise, production for a plot is zero. Therefore the intuition for production at the plot level is identical to that of drilling: Proximity to state land may either decrease the production on nearby federal land (substitution effect) or increase it (total expected cost effect).

Well-level production: For a plot to have a well, it must have drilling, and therefore predictions about well-level production must account for what plots are selected for drilling and whether the wells drilled are initial exploratory wells or follow-up wells. The substitution and the total cost effects both affect this selection:

On one hand, the substitution effect implies that a federal well that is close to state land is more likely to be a follow-up well relative to a well drilled on federal land far from state land, which is more likely to be an initial exploratory well. Because there is a learning value to drilling an exploratory well but not to drilling a follow-up well, the minimum expected reserves required to drill a follow-up well will be higher, implying that follow-up wells will tend to have higher production than exploratory wells. Therefore proximity to state land will lead to higher average production for federal-land wells.

On the other hand, the total expected cost effect implies that proximity to state land lowers the threshold for which there is any drilling because of the shifts in the $\pi_1 = 0$ and the $\pi_2 = 0$ indifference curves. The shift in the $\pi_2 = 0$ curve means that exploratory wells drilled on federal land close to state land will have on average lower expected production than federal wells far from state land, which in turn translates into lower average productivity. Furthermore, the shift in the $\pi_1 = 0$ line means follow-up wells drilled on federal land close to state land will be more likely to have lower expected production initially than federal follow-up wells far from state land, which also translates into lower average productivity. These imply that proximity to state land will lead to lower average production for federal-land wells.

Dominant effect may depend on outcome: Which effect dominates may change depending on which outcome is being examined. For example, the online appendix shows that if G is restricted such that μ_1 is always equal to μ_2, proximity to state land always reduces the likelihood that federal land is the site of the exploratory well (substitution effect dominates), but may either decrease or increase the probability that federal land is ever drilled (either substitution effect or total expected cost effect dominates).

Extensions. — I first briefly discuss a number of other policies and their predicted spillover effects, followed by a discussion of how the model changes with common pools and multiple firms. Further details are in the online appendix.

Royalties: This model is easily extended to royalties with no change in intuition, but with the opposite sign, as state royalties are higher than federal royalties. Holding all else equal, proximity to state land either increases drilling on federal land (substitution effect) or decreases drilling on federal land (a total expected royalty effect).

Primary terms: Because federal primary terms are longer than state primary terms, a firm that is leasing both federal and state land is likely to have its state primary term expire first. Because drilling a productive well allows the firm to retain the lease, the firm will prefer to drill first on the lease that expires first, all else equal. As this initial well may or may not be productive enough to warrant drilling a follow-up well on federal land, proximity to state land will decrease drilling on federal land.

Delays: Because $\delta < 1$, the firm prefers to drill earlier. If there are delays in processing drilling approvals for federal land, then proximity to state land will in some cases cause the firm to drill first on state land. As not all exploratory drilling leads to follow-up drilling, this will reduce the likelihood that nearby federal land is ever drilled.[10]

Multiple firms: When two different firms have the right to drill on plot 1 and plot 2 respectively, each firm faces a trade-off between drilling now and waiting for the other firm to drill. Waiting is valuable if the other firm drills as the other firm will reveal information about the productivity of the region (Hendricks and Kovenock, 1989). While the model is very different from the single-firm model, theoretical results are similar. On one hand, a substitution-like effect can result because the cost profile affects the order of drilling: Comparing the federal-federal case with the state-federal case, low costs on plot 1 in the state-federal case increase the probability of drilling on plot 1, which incentivizes the firm on plot 2 to wait, decreasing the

[10] While both the primary term and the delay model suggest that proximity to state land *decreases* drilling on federal land, a model with both primary terms and delays may imply that proximity to state land *increases* drilling on federal land. See the online appendix.

likelihood of ever drilling on plot 2. On the other hand, an effect similar to the total expected cost can also result: In cases where expected productivity is low, low costs on plot 1 in the state-federal case will lead to drilling on plot 1 that would not happen in the federal-federal case. Sometimes that initial well is productive and leads to a follow-up well drilled on nearby federal plot 2.

Common pools: If common pools are present, then the first well drilled reduce the potential production of the undrilled plot, which decreases the profitability of drilling the undrilled plot.[11] Therefore, common pools may exacerbate the substitution effect and dampen the expected cost effect. I discuss common pools later in the paper as well as in the online appendix.

III. Empirical Preliminaries

Motivated by the model predictions that state land policies have a theoretically ambiguous effect on drilling and production outcomes on nearby federal land, I next turn to empirics. I first discuss the natural experiment that led to exogenous variation in land ownership. Next I discuss data sources and descriptive statistics. Third, I discuss the intent-to-treat econometric specification that I use to identify spillovers. I show evidence that the natural experiment in land assignment predicts current ownership and satisfies the exclusion restriction.

A. The Natural Experiment

Identifying the impact of spillovers of state policy requires variation in the proximity of federal land to state land that is orthogonal to geology and other factors that affect the profitability of drilling. The Land Ordinance of 1785 and its later amendments provided such variation by specifying rules of land mapping and land allocation in newly acquired US territories. Land was to be mapped into six mile by six mile squares known as townships, and further subdivided into 36 square-mile plots known as sections. Sections were numbered boustrophedonically from 1 to 36 as shown in Figure 1. When a new state was created, sections 16 and 36 of each township would be transferred from federal to state ownership.[12] State governments could use these lands to generate revenue through activities like oil and gas leasing.[13] In arid regions like southwest Wyoming with little private demand for land, the federal government often retained ownership of the remaining land, leading to a persistent pattern of federal and state ownership.

The regular pattern of land assignment assures that geology is uncorrelated with whether a plot is in federal or state ownership. Crucially, it also assures

[11] In a multi-firm model, common pools also can lead firms to extract too quickly, which leaves oil in the ground (Libecap and Wiggins, 1985).

[12] Initially the Land Ordinance of 1785 specified that only the 16th section would be transferred to state ownership. Later amendments allowed Wyoming to receive both the 16th and 36th sections. Some other states received either three or four sections per township depending on the date of statehood. See Souder and Fairfax (1996) for more details.

[13] Initially, such lands were usually designated to be sites for schools. However in later years, the sites instead were leased to generate revenue used for state education funds (Souder and Fairfax, 1996).

that geology is uncorrelated with the proximity of a federal plot to state land. This provides the variation need to identify spillover effects. For example, Figure 1 shows that section 13 lies far from state land while section 15 lies close. As #13 sections are not expected to have higher or lower oil reserves than #15 sections, the average difference in outcomes between #13 sections and #15 sections can be attributed to the spillover effect of state land policies.

B. *Wyoming and the Greater Green River Basin*

I use data from Wyoming. Wyoming has extensive oil and gas data with drilling data dating back to 1900 and monthly well production data dating back to 1978. Data are taken from the Wyoming Oil and Gas Conservation Commission (WOGCC) with additional light editing by the US Geological Survey (USGS) to improve accuracy (Biewick, 2011). I also use GIS data on mineral ownership and physical geographic features. The Online Appendix Subsection A.5 discusses data sources and data set construction.

I limit the sample to the Greater Green River Basin (GGRB) of Wyoming.[14] The GGRB is a geologically productive region, with 12 of the 100 largest natural gas fields in the US, and 2 of the 100 largest oil fields (Energy Information Agency, 2010). The vast majority if drilling is of vertical wells that do not span multiple sections. As the GGRB is a mostly arid region, the original federal-state ownership pattern has persisted largely unchanged until today. The notable exception is the region within 20 miles of the transcontinental railroad, where odd-numbered sections were transferred to the Union Pacific in the 1860's (Larson, 1990). I exclude this region from the analysis.

Within the GGRB it is unlikely that there are common pools that significantly distort production. This is due both to the geology of the GGRB and to institutional spacing rules. Geologically, the GGRB has relatively impermeable source rock, which limits oil and gas migration, and therefore limits the radius of source rock from which a well can produce. Institutionally, Wyoming (and all other oil and gas producing US states) have implemented spacing rules that limit how closely wells can be drilled to each other in order to prevent the drainage areas of neighboring wells from overlapping, thereby preventing common pools.(Flanery and Morgan, 2011; Interstate Oil and Gas Compact Commission, 2015; Edwards, O'Grady and Jenkins, 2016).[15] In the online appendix, I discuss evidence on permeability, drainage areas, and spacing rules in the GGRB to show that spacing rules appear to be sufficient to prevent well drainage areas from overlapping.

[14] A map of the GGRB is in the Online Appendix Subsection A.5.

[15] In Wyoming, for example, natural gas wells are limited to 1 per square mile or 1 per 1/4 mile, and state regulators typically require firms to submit geological evidence that drainage areas are small relative to the spacing rule before allowing firms to drill more closely spaced wells.

Table 1—Summary statistics for sections.

	mean	st.dev.	median	5th perc	95th perc
is 16/36	0.06	0.23	0.00	0.00	1.00
distance to closest 16 or 36	1.63	0.68	1.67	0.00	2.90
square miles	0.98	0.11	1.00	0.91	1.02
fraction state mineral	0.06	0.22	0.00	0.00	0.69
fraction federal mineral	0.86	0.29	1.00	0.01	1.00
had wildcat well by 2010	0.10	0.30	0.00	0.00	1.00
any well by 2010	0.22	0.42	0.00	0.00	1.00
any productive well by 2010	0.14	0.35	0.00	0.00	1.00
observations	12,549				

C. *Sample and Descriptive Statistics*

I construct a sample of all sections in the GGRB. I exclude sections that are more than 3.2 miles away from the closest 16/36 section in Wyoming, as well as sections that are within 20.5 miles of the transcontinental railroad.[16] This leaves a sample of 12,549 sections, with 696 sections that are numbered either 16 or 36.

Summary statistics of this sample are in Table 1. This region is fairly geologically productive, with 14% of sections in the sample having a productive oil or gas well and 22% have had some well drilled. Ten percent of sections are reported to have a "wildcat" well—the industry term for an exploratory well that the firm does not believe will produce from a known oil or gas field. Overall, about 86% of the land is in federal mineral ownership and 6% is in state mineral ownership, with the rest privately owned. Table 2 shows summary statistics for wells drilled in the area. Wells are mostly gas (64%) or dry (22%). Twelve percent of wells are wildcat wells.

D. *Empirical Specification and Inference*

The empirical specification tests how outcomes differ depending on whether the section was assigned to be in state ownership (section 16 or 36) as well as how close the section is to the closest 16 or 36 section. Using the section as the unit of observation, I employ the following regression specification:

$$Y_i = \alpha + \beta_{16/36} \cdot 1_i(16/36) + \sum_{d \in \{1, \sqrt{2}, 2, \sqrt{5}\}} \beta_d \cdot 1_i(\text{closest } 16/36 \approx d \text{ miles away}) + \varepsilon_i \tag{3}$$

Here, Y_i is an outcome of interest, such as whether drilling ever happened on a given section i. Proximity d to the closest 16 or 36 section is measured as

[16] Distances between sections are measured as the distance between section centroids.

TABLE 2—SUMMARY STATISTICS FOR WELLS.

	mean	st.dev.	median	5th perc	95th perc
on 16/36	0.07	0.25	0.00	0.00	1.00
oil well	0.10	0.30	0.00	0.00	1.00
gas well	0.64	0.48	1.00	0.00	1.00
oil and gas	0.01	0.10	0.00	0.00	0.00
dry or unreported	0.22	0.42	0.00	0.00	1.00
wildcat	0.12	0.32	0.00	0.00	1.00
subsurface reported	0.33	0.47	0.00	0.00	1.00
drill year	1988	23.00	1998	1937	2010
observations	13,826				

the distance between the section centroid and the centroid of the closest 16 or 36 section. Because of the grid structure of sections, most sections are approximately 1, $\sqrt{2}$, 2, $\sqrt{5}$, or 3 miles from the closest 16 or 36 section.[17] The omitted category is $d = 3$ miles. I also employ a simpler regression where I regress Y_i only on $1_i(16/36)$ and a constant.

I use this regression specification in two ways. In section III.E, I use it with current ownership and physical characteristics as outcome variables to show that the right-hand side variables of Equation 3 are valid instruments. Then in section IV, I use the same regression specification as an intent-to-treat specification to examine how ownership and proximity to state land affect drilling and production.

Proper inference requires accounting for spatial correlation. To estimate how far spatial correlation extends, I construct a data set of all pairs of sections in Wyoming. I find that whether there is drilling on one section predicts whether there is drilling on another section only if the two sections are within 20 miles of each other (see Figure 4). Therefore I use Conley (1999) standard errors and allow for correlation between ε_i and ε_j only if section i and section j are within 20 miles of each other.[18]

E. Validity of Identification

Within this sample of sections, whether a section is 16 or 36 is a strong predictor of current mineral ownership. Figure 2 is a map of ownership within part of the GGRB that shows that the ownership pattern is fairly strong. To quantify the strength of the ownership pattern, Table 3, columns 1 and 3, compares 16/36 and non 16/36 sections where the dependent variable is either the fraction of land in federal ownership or fraction of land in state ownership. I find that a non-16/36

[17]Some exceptions exist due to the curvature of the earth.

[18]$\text{var}(\widehat{\beta}) = (\mathbf{x}'\mathbf{x})^{-1}\mathbf{x}'\Sigma\mathbf{x}(\mathbf{x}'\mathbf{x})^{-1}$. Because the true Σ is not observable, we approximate $\Sigma \approx N/(N-k)\cdot\widehat{\Sigma}$, where N is the number of observations, k is the number of parameters, and the ij^{th} element of $\widehat{\Sigma}$ is $\widehat{\sigma_{ij}}$. As recommended by Conley (2008), I use a uniform weight: $\widehat{\sigma_{ij}} = 1(d_{ij} \leq 20)\cdot\widehat{\varepsilon_i}\widehat{\varepsilon_j}$, where $\widehat{\varepsilon_i}$ is the residual for observation i and $d(i,j)$ is the distance in miles between the centroids of sections i and j.

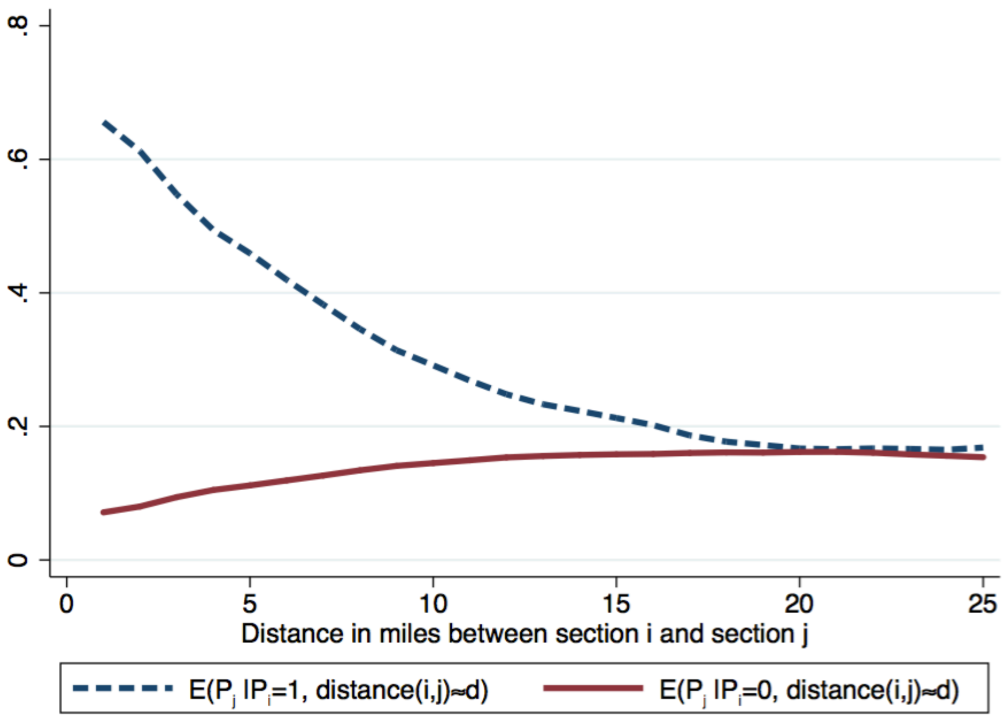

FIGURE 4. A GRAPH SHOWING THE EXTENT TO WHICH WHETHER A SECTION EVER HAD A PRODUCTIVE WELL PREDICTS WHETHER ANOTHER SECTION d MILES AWAY ALSO HAS A PRODUCTIVE WELL. P_i IS INDICATOR VARIABLES THAT INDICATES WHETHER SECTION i HAD A PRODUCTIVE WELL, AND d IS THE DISTANCE IN MILES BETWEEN SECTIONS i AND j.

section is predicted to be only 2% state mineral lands on average, while a 16/36 section is predicted to be 80% in state ownership.[19] In contrast, a non-16/36 section is predicted to be 90% in federal ownership, while a 16/36 section is predicted to be only 18% in federal ownership.

I also find that current mineral ownership is not strongly correlated with proximity to 16/36 sections. This is important because correlation between ownership and proximity to 16/36 sections would make it difficult to identify whether differences in drilling outcomes for sections closer to versus further away from 16/36 sections are driven by spillovers from state land policy or by differences in ownership. In Table 3 columns 2 and 4, I regress ownership fraction on the full set of right-hand

[19]In the online appendix, I discuss the 16/36 sections that are not in state ownership. I show that most of them are in the northwest part of the GGRB. I show that empirical results are robust to excluding this part of the GGRB.

Table 3—Regressions of the fraction of a section that is in state ownership (columns 1 and 2) or in federal ownership (columns 3 and 4) as a function of whether a section is numbered 16 or 36, and proximity of the section to the closest section numbered 16 or 36. The first p value is a the joint test that all coefficients—except for the constant—are equal to zero. The second p value is the joint test that coefficients for 1 mile, $\sqrt{2}$ miles, 2 miles, and $\sqrt{5}$ miles are all equal to zero. I use Conley standard errors with a uniform weight and maximum correlation distance of 20 miles.

	(1) State	(2) State	(3) Federal	(4) Federal
is 16/36	0.781	0.781	-0.727	-0.715
	(0.067)	(0.067)	(0.070)	(0.071)
$\approx$ 1 mile away		0.004		0.011
		(0.004)		(0.009)
$\approx \sqrt{2}$ miles away		-0.001		0.017
		(0.004)		(0.011)
$\approx$ 2 miles away		-0.002		0.011
		(0.002)		(0.008)
$\approx \sqrt{5}$ miles away		0.001		0.011
		(0.003)		(0.010)
constant	0.019	0.019	0.904	0.892
	(0.006)	(0.006)	(0.021)	(0.026)
R squared	0.668	0.668	0.326	0.326
p value joint test		0.000		0.000
p value non-16/36		0.073		0.149
Observations	12549	12549	12548	12548

side variables in equation 3. I find no relationship of federal land ownership with proximity to 16/36 sections. I do find some correlation between state ownership and proximity to 16/36 sections ($p < 10\%$), where sections at a medium distance from 16/36 sections are very slightly less likely to be in state ownership. Therefore I include robustness results where I limit analysis to regions where the federal-state ownership pattern has remained particularly robust.[20]

Another important check for instrument validity is to check for evidence that the instruments satisfy the exclusion restriction—that they are not correlated with other factors that affected oil and gas productivity. I do not find significant evidence of such correlations. Table 4 shows that elevation and elevation range are not strongly correlated with 16/36 sections and proximity to 16/36 sections. Similarly, Table 5 shows that a variety of social and economic outcomes are not correlated with the instrument, including whether the section includes a settlement or municipality, a fence, dry crops, or a surface mine. The only two outcome variables that are correlated are wetland status and whether there are irrigated crops: sections further from 16/36 are more likely to have irrigated crops and contain wetlands. As a robustness check in the next section, I add controls for these above-ground characteristics and find that they have very little effect on coefficients. As only a very small fraction of sections have wetlands or irrigated crops, these characteristics can explain very little of the variation in drilling and production outcomes. Finally, in the online appendix, I discuss evidence on roads to show that while ex-post road presence is correlated with the instruments, roads do not explain the drilling and production results in the next section.

IV. Drilling and Production Results

Next I examine how drilling and production depend on whether a section is a 16/36 section and how close it is to the closest 16/36 section. I use the regression specification in equation (3). Here, the coefficient $\beta_{16/36}$ can be interpreted as the intent-to-treat effect of assigning land to state ownership. The coefficients β_1, $\beta_{\sqrt{2}}$, β_2, and $\beta_{\sqrt{5}}$ can be interpreted as the intent-to-treat spillover effects of state land on federal land.

A. Exploratory Drilling

To determine how land ownership affects how firms search for and drill for oil, I regress an indicator for whether a section is ever the site of a wildcat well by 2010 on the set of right-hand side variables in Equation 3. Results are in Table 6 columns

[20] To determine which regions have the most robust land ownership, I calculate a section-level measure of fit as the the fraction of a section that is in state ownership if the section is 16/36 and the fraction of a section that is in federal ownership if the section is not 16/36. Then for each section, I identify the closest 16/36 section and the closest 13/33 section. I compute a 16/36 fit score, which is the average fit score over all sections matched to a given 16/36 section, as well as a 13/33 fit score, which is the average fit score over all sections matched to a given 13/33 section. I determine that a section is in a region with good fit if both its 16/36 fit score and its 13/33 fit score are above 90%.

TABLE 4—COMPARING MEAN ELEVATION, RANGE OF ELEVATION WITHIN SECTION, THE FRACTION OF THE SECTION WITH ANY WETLANDS, AND THE FRACTION OF THE SECTION THAT WAS VISUALLY CHECKED BY A SURVEYOR (RATHER THAN ESTIMATED USING GEOSPATIAL METHODS). ELEVATION DATA IS NOT AVAILABLE FOR ALL SECTIONS. MOST SECTIONS MISSING ELEVATION DATA ARE ON THE SOUTHERN BORDER WITH UTAH. THE FIRST P VALUE IS A THE JOINT TEST THAT ALL COEFFICIENTS—EXCEPT FOR THE CONSTANT—ARE EQUAL TO ZERO. THE SECOND P VALUE IS THE JOINT TEST THAT COEFFICIENTS FOR 1 MILE, $\sqrt{2}$ MILES, 2 MILES, AND $\sqrt{5}$ MILES ARE ALL EQUAL TO ZERO. I USE CONLEY STANDARD ERRORS WITH A UNIFORM WEIGHT AND MAXIMUM CORRELATION DISTANCE OF 20 MILES.

	(1)	(2)	(3)	(4)
	mean elev	range elev	wetlands	check
is 16/36	-20.294	-0.665	-0.024	-0.004
	(19.200)	(3.841)	(0.008)	(0.011)
$\approx$ 1 mile away	1.178	4.877	-0.015	-0.001
	(13.490)	(3.650)	(0.008)	(0.006)
$\approx \sqrt{2}$ miles away	-3.874	1.555	-0.017	-0.004
	(12.967)	(2.725)	(0.008)	(0.005)
$\approx$ 2 miles away	-4.799	4.052	-0.007	-0.004
	(12.984)	(3.918)	(0.006)	(0.012)
$\approx \sqrt{5}$ miles away	6.520	4.259	-0.013	0.002
	(20.324)	(3.802)	(0.007)	(0.010)
constant	2102.140	80.981	0.073	0.228
	(24.606)	(7.487)	(0.013)	(0.059)
R squared	0.000	0.000	0.001	0.000
p value joint significance	0.095	0.108	0.000	0.489
p value non-16/36	0.316	0.581	0.189	0.489
Observations	12506	12506	12549	12549

TABLE 5—REGRESSION OF LAND COVERAGE MEASURES WITHIN A SECTION. DEPENDENT VARIABLES ARE FRACTION OF A SECTION WITH ANY SETTLEMENT (COLUMN 1), WHETHER THERE IS ANY MUNICIPALITY (COLUMN 2), WHETHER THERE IS ANY FENCING WITHIN THE SECTION (COLUMN 3), FRACTION OF SECTION WITH DRY CROP (COLUMN 4), FRACTION OF SECTION WITH IRRIGATED CROPS (COLUMN 5), AND FRACTION OF A SECTION WITH A SURFACE MINE (COLUMN 6). THE FIRST P VALUE IS A THE JOINT TEST THAT ALL COEFFICIENTS—EXCEPT FOR THE CONSTANT—ARE EQUAL TO ZERO. THE SECOND P VALUE IS THE JOINT TEST THAT COEFFICIENTS FOR 1 MILE, $\sqrt{2}$ MILES, 2 MILES, AND $\sqrt{5}$ MILES ARE ALL EQUAL TO ZERO. I USE CONLEY STANDARD ERRORS WITH A UNIFORM WEIGHT AND MAXIMUM CORRELATION DISTANCE OF 20 MILES.

	(1) settled	(2) muni	(3) fence	(4) dry crop	(5) irrig	(6) mine
is 16/36	-0.001	-0.003	-0.016	-0.001	-0.007	-0.001
	(0.001)	(0.003)	(0.017)	(0.000)	(0.006)	(0.000)
$\approx$ 1 mile away	-0.001	-0.002	-0.006	-0.001	-0.004	-0.000
	(0.001)	(0.003)	(0.014)	(0.000)	(0.005)	(0.000)
$\approx \sqrt{2}$ miles away	-0.001	-0.002	-0.009	-0.000	-0.004	-0.000
	(0.001)	(0.003)	(0.016)	(0.000)	(0.005)	(0.000)
$\approx$ 2 miles away	-0.000	0.000	-0.010	-0.000	0.002	-0.000
	(0.000)	(0.002)	(0.010)	(0.001)	(0.004)	(0.000)
$\approx \sqrt{5}$ miles away	-0.001	0.000	-0.015	-0.000	-0.001	-0.000
	(0.000)	(0.002)	(0.016)	(0.001)	(0.004)	(0.000)
constant	0.001	0.004	0.317	0.001	0.037	0.001
	(0.001)	(0.003)	(0.047)	(0.001)	(0.014)	(0.000)
R squared	0.001	0.000	0.000	0.000	0.000	0.000
p value joint sig	0.351	0.255	0.846	0.229	0.000	0.556
p value non-16/36	0.351	0.134	0.861	0.265	0.134	0.355
Observations	12549	12549	12549	12549	12549	12549

1-4. 16/36 sections are 42 percent more likely to have wildcat wells relative to non-16/36 sections (column 1). This masks significant heterogeneity among non-16/36 sections: Column 2 shows that of the non-16/36 sections, sections 3 miles from the closest 16/36 section are the most likely to have exploratory drilling (10.9%) whereas sections that are 2 miles from the closest 16/36 section are the least likely (8.7%). I reject the null hypothesis that the coefficients $\beta_1, \beta_{\sqrt{2}}, \beta_2$, and $\beta_{\sqrt{5}}$ are all equal with a p value of 0.033. Results are similar when controlling for physical characteristics and township fixed effects (column 3). When limited to the sample with the strongest land ownership patterns, coefficient estimates are very similar although the null hypothesis of no spillovers—that $\beta_1, \beta_{\sqrt{2}}, \beta_2$, and $\beta_{\sqrt{5}}$ are all equal to zero—cannot be rejected (column 4).[21]

These results suggest the spillover effect: Firms seem to be sometimes shifting their exploratory drilling to state land, such that sections that are between 1 and $\sqrt{5}$ miles from 16/36 sections have lower exploratory drilling than sections that are 3 miles from 16/36 sections.

B. *Overall Drilling*

Next I examine whether drilling ever happens on a section by 2010. Table 6 column 5 shows that 16/36 sections were 19 percent more likely to have any drilling by 2010 than non-16/36 sections. However this again masks significant heterogeneity among non-16/36 sections: Column 6 shows that sections 3 miles from the closest 16/36 section are the most likely to have drilling (24.9% probability) whereas sections 2 miles from the closest 16/36 section are the least likely (21.7% probability). These coefficients are significant at the 5% level. Coefficients are similar sizes and β_1 through $\beta_{\sqrt{5}}$ are all statistically significant when controlling for physical characteristics and township fixed effects (column 7). When limited to the area where ownership patterns have remained the strongest, I reject that that β_1 through $\beta_{\sqrt{5}}$ are all equal to zero (p value = 2.5% in column 8).

Again, these results suggest that the substitution effect is dominating, as sections that are closer to 16/36 sections are less likely to have drilling than sections that are far from 16/36 sections. I do not find that drilling probabilities on 16/36 sections and sections ≈ 3 miles away from 16/36 sections are significantly different.

[21]One concern is that wildcat wells as measured in the data are inaccurate because wells that were originally wildcats were recoded as belonging to a particular field if they were found to be productive. However I find that some wildcat wells are reported to be productive, which implies re-categorization is limited. To account for cases where wildcat wells are recoded, I construct an alternative measure of exploratory wells where I define a well to be exploratory if either it is listed as a wildcat well or if it is drilled in the first year of drilling for the set of wells that are in the same field. Estimates using this alternate specification are similar.

Table 6—Regressions of the probability of wildcat (exploratory) well on a section by 2010 (columns 1-4) or that a section ever had a wildcat (exploratory) well by 2010 (columns 5-8). The first p value is the test that the coefficients for 16/36 and 1, $\sqrt{2}$, 2, and $\sqrt{5}$ miles away are all equal to zero. The second p value is the test that the coefficients for 1, $\sqrt{2}$, 2, and $\sqrt{5}$ miles away all equal to zero. Physical characteristics that are controlled for in columns 3 and 6 are township fixed effects, mean elevation, elevation range, whether elevation data was missing, presence of wetlands, and presence of irrigated crops. Columns 5 and 8 are limited to the sample where the land ownership pattern has remained particularly strong. I use Conley standard errors with a uniform weight and maximum correlation distance of 20 miles. A graph of coefficients in column 2 is in Online Appendix Figure A4; a graph of coefficients in column 6 is in Online Appendix Figure A5.

	(1) wildcat	(2) wildcat	(3) wildcat	(4) wildcat	(5) drill	(6) drill	(7) drill	(8) drill
is 16/36	0.041	0.031	0.029	0.024	0.043	0.016	0.015	0.019
	(0.014)	(0.013)	(0.013)	(0.020)	(0.014)	(0.017)	(0.017)	(0.018)
$\approx$ 1 mile away		-0.004	-0.004	-0.009		-0.028	-0.031	-0.024
		(0.008)	(0.008)	(0.010)		(0.011)	(0.009)	(0.009)
$\approx \sqrt{2}$ miles away		-0.008	-0.008	-0.008		-0.028	-0.028	-0.021
		(0.008)	(0.007)	(0.011)		(0.014)	(0.010)	(0.015)
$\approx$ 2 miles away		-0.022	-0.021	-0.021		-0.032	-0.031	-0.017
		(0.008)	(0.007)	(0.012)		(0.012)	(0.008)	(0.008)
$\approx \sqrt{5}$ miles away		-0.008	-0.010	-0.010		-0.026	-0.026	-0.021
		(0.009)	(0.009)	(0.014)		(0.014)	(0.009)	(0.018)
constant	0.098	0.109		0.110	0.222	0.249		0.257
	(0.011)	(0.011)		(0.012)	(0.040)	(0.045)		(0.042)
physical chars.	No	No	Yes	No	No	No	Yes	No
R squared	0.001	0.002	0.108	0.001	0.001	0.001	0.351	0.001
p value joint test		0.005	0.007	0.090		0.001	0.000	0.042
p value non-16/36		0.033	0.007	0.337		0.037	0.000	0.025
Observations	12549	12549	12549	7869	12549	12549	12549	7869

C. Section-level Production

I next examine section-level production. I aggregate total 1978-2010 production for all wells drilled on a section between 1978 and 2010.[22] I measure three types of production: natural gas, oil, and an oil and gas aggregate measure called barrel-of-oil equivalent production (BOE).[23] As section-level production has both a long right tail and many zeros, it is useful to transform it such that outliers are less likely to drive coefficient estimates and all observations with zero production are included. To do this, I use the inverse hyperbolic sine transformation recommended by MacKinnon and Magee (1990).[24] Regression estimates are in Table 7.

Here, point estimates suggest that the substitution effect dominates, but the results are not statistically significant. For example, column 1 shows that 16/36 sections and sections 3 miles away have the same level of BOE production, while sections 1 to $\sqrt{5}$ miles away have slightly less production. Controlling for township fixed effects in column 2 increases the R squared significantly but has little effect on the precision of the estimates. Similar results hold when measuring gas production (columns 3 and 4) and oil production (columns 5 and 6).

Examining the cdf of section-level production, I find evidence that land ownership and spillovers seem to have the most effect on places with lower but positive geological productivity but little effect on places with the highest geological productivity. In Figure 5, I graph the cdf of total BOE production from 1978 to 2010 among three different types of sections: 16/36 sections, sections that are 1–$\sqrt{5}$ miles away, and sections that are 3 miles away. I find that for high levels of production (BOE above 1 million) the cdfs are very similar for all three types of sections. This implies that for high-productivity regions, government policies have very little impact on production. In contrast, for values of BOE between zero and about 100,000, the cdf for $1-\sqrt{5}$ sections is significantly above that of the 16/36 and the 3 mile sections, which track each other closely. This shows that substitution effects seem to have the greatest effect where reserves are low but still positive.

D. Well-level Productivity

Next I examine well-level production. In particular, I measure the log of the first 24 months of production, for all wells drilled between 1978 and 2010. I use this measure because many wells have not ended their production lifetimes, and the first 24 months of production is a good proxy for total production.[25] Regression results

[22] I use 1978 because it is the first year that monthly well production was recorded and 2010 as it is the last year available in the cleaned USGS version of the WOGCC data.

[23] Barrel-of-oil equivalent aggregates oil and natural gas production together, where natural gas is converted into barrel-of oil equivalent production using the rule that 6 MCF of gas has approximately the same energy content as 1 barrel of oil. Wyoming data on oil production includes production of natural gas liquids, as natural gas liquids and oil are not separated from each other prior to production metering.

[24] This transformation takes production q and constructs a new variable $\tilde{q} = \sinh^{-1}(q) = \log(q + \sqrt{q^2+1})$.

[25] As well production often has an approximately exponential decline, the log of any initial period of production will be approximately proportional to log total production (Arps, 1945).

	(1) BOE	(2) BOE	(3) Gas	(4) Gas	(5) Oil	(6) Oil
is 16/36	0.00	-0.00	0.04	0.04	0.01	0.00
	(0.14)	(0.15)	(0.16)	(0.17)	(0.13)	(0.12)
$\approx$ 1 mile away	-0.25	-0.27	-0.25	-0.28	-0.20	-0.21
	(0.13)	(0.13)	(0.16)	(0.15)	(0.11)	(0.10)
$\approx \sqrt{2}$ miles away	-0.19	-0.19	-0.19	-0.20	-0.14	-0.15
	(0.14)	(0.13)	(0.16)	(0.15)	(0.11)	(0.11)
$\approx$ 2 miles away	-0.18	-0.19	-0.17	-0.19	-0.12	-0.13
	(0.11)	(0.11)	(0.13)	(0.13)	(0.09)	(0.10)
$\approx \sqrt{5}$ miles away	-0.21	-0.22	-0.22	-0.23	-0.14	-0.15
	(0.15)	(0.14)	(0.17)	(0.16)	(0.12)	(0.11)
constant	1.56		1.71		1.09	
	(0.44)		(0.51)		(0.33)	
township FE	No	Yes	No	Yes	No	Yes
R squared	0.00	0.47	0.00	0.47	0.00	0.47
p value joint test	0.39	0.32	0.47	0.29	0.21	0.18
p value non-16/36	0.32	0.22	0.42	0.35	0.29	0.15
Observations	12549	12549	12549	12549	12549	12549

Table 7—Regression table where dependent variable is MacKinnon-Magee transform of total 1978-2010 production for wells drilled between 1978 and 2010, aggregated to the section level. BOE refers to barrel-of-oil equivalent production. The first p value is the test that the coefficients for 16/36 and 1, $\sqrt{2}$, 2, and $\sqrt{5}$ miles away are all equal to zero. The second p value is the test that the coefficients for 1, $\sqrt{2}$, 2, and $\sqrt{5}$ miles away all equal to zero. I use Conley standard errors with a uniform weight and maximum correlation distance of 20 miles. A graph of coefficients in column 2 is in Online Appendix Figure A6.

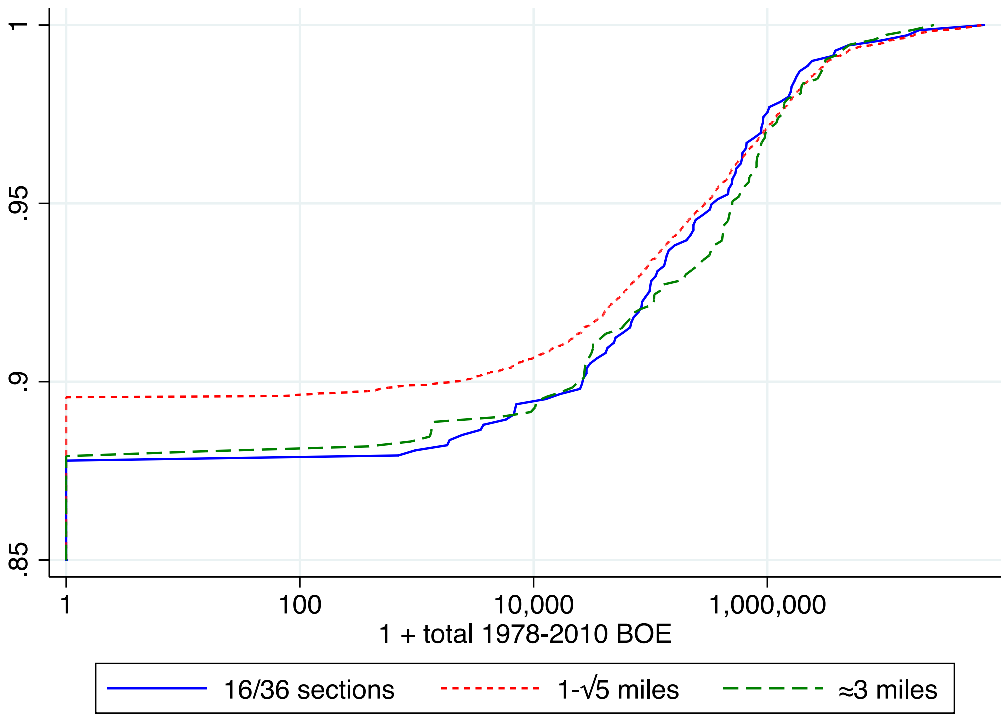

FIGURE 5. CDF OF TOTAL SECTION-LEVEL 1978-2010 BOE PRODUCTION FOR ALL WELLS DRILLED BETWEEN 1978 AND 2010, COMPARING 16/36 SECTIONS, SECTIONS 1-$\sqrt{5}$ MILES AWAY, AND SECTIONS 3 MILES AWAY.

are robust to using the first 12 or the first 36 months of production.

I find that that wells on 16/36 sections have lower average production than those on sections 1-$\sqrt{5}$ miles away, which in turn have lower average production than those on sections 3 miles away. Regression estimates are in Table 8 and are included for BOE (columns 1 and 2), Gas (columns 3 and 4), and Oil (columns 5 and 6). The BOE and Gas specifications that include township fixed effects show that 16/36 wells have lower average production than those that are $1-\sqrt{5}$ miles away, which in turn have lower production than wells 3 miles away from 16/36 sections, and that these differences are statistically significant.

The results here show evidence of the total expected cost effect. Wells close to 16/36 sections have lower average production than wells far from 16/36 sections, suggesting that lower costs on state land lead to exploratory drilling on state land with low expected productivity, which in some cases led to follow-up drilling on nearby federal land that also had low expected productivity.

In the Online Appendix Subsection A.6, I test whether common pools and multiple operators are driving these production patterns. Common pool inefficiencies can result when multiple firms operate in the same region. Such common pool

TABLE 8—REGRESSIONS OF LOG WELL-LEVEL PRODUCTION FOR THE FIRST 24 MONTHS OF PRODUCTION FOR WELLS DRILLED BETWEEN 1978 AND 2010. BOE REFERS TO BARREL-OF-OIL EQUIVALENT PRODUCTION. THE FIRST P VALUE IS THE TEST THAT THE COEFFICIENTS FOR 16/36 AND 1, $\sqrt{2}$, 2, AND $\sqrt{5}$ MILES AWAY ARE ALL EQUAL TO ZERO. THE SECOND P VALUE IS THE TEST THAT THE COEFFICIENTS FOR 1, $\sqrt{2}$, 2, AND $\sqrt{5}$ MILES AWAY ALL EQUAL TO ZERO. I USE CONLEY STANDARD ERRORS WITH A UNIFORM WEIGHT AND MAXIMUM CORRELATION DISTANCE OF 20 MILES. A GRAPH OF COEFFICIENTS IN COLUMN 2 IS IN ONLINE APPENDIX FIGURE A7.

	(1) BOE	(2) BOE	(3) Gas	(4) Gas	(5) Oil	(6) Oil
is 16/36	-0.48	-0.48	-0.62	-0.59	-0.23	-0.21
	(0.30)	(0.15)	(0.33)	(0.19)	(0.27)	(0.03)
$\approx$ 1 mile away	-0.18	-0.12	-0.22	-0.15	-0.09	-0.08
	(0.11)	(0.09)	(0.10)	(0.05)	(0.15)	(0.07)
$\approx \sqrt{2}$ miles away	-0.17	-0.20	-0.21	-0.22	0.01	-0.15
	(0.08)	(0.08)	(0.10)	(0.04)	(0.13)	(0.07)
$\approx$ 2 miles away	-0.23	-0.13	-0.19	-0.09	-0.11	-0.08
	(0.15)	(0.08)	(0.14)	(0.05)	(0.18)	(0.06)
$\approx \sqrt{5}$ miles away	-0.25	-0.20	-0.28	-0.18	-0.08	-0.13
	(0.07)	(0.06)	(0.11)	(0.05)	(0.12)	(0.07)
constant	11.29		13.01		8.24	
	(0.49)		(0.52)		(0.52)	
township FE	No	Yes	No	Yes	No	Yes
R squared	0.00	0.50	0.00	0.52	0.00	0.49
p value joint test	0.25	0.00	0.09	0.00	0.00	0.15
p value non-16/36	0.00	0.00	0.00	0.00	0.35	0.15
Observations	7800	7800	7588	7588	7317	7317

inefficiencies may be more likely in the regions where federal and state land border each other, as the heterogeneity in ownership may lead to greater number of firms operating.[26] Common pool inefficiencies may lead the the firms to extract inefficiently fast, leading to faster declines in production and overall lower production (Libecap and Wiggins, 1984). Therefore one alternative explanation for the results in Table 8 is a higher likelihood of common pools inefficiencies for wells on state land and nearby federal land. However in the online appendix I find that state and nearby federal land do not have a higher number of operating firms relative to federal land far from state land. I also do not find evidence that well production declines faster for wells that are located on state and nearby federal land relative to wells that are far from state land.

E. Policy Changes

If NEPA in 1970 lead to a major shift in profitability of drilling on federal land, then we should see it reflected in changing spatial drilling patterns. The effects will likely be delayed somewhat due both to delays in implementing policy and to the fact that many leases are not drilled until the primary term is close to expiring. In Figure 6 I graph the probability that a section has ever had drilling by a given year for years ranging from 1900 to 2010. I compare 16/36 sections, $1-\sqrt{5}$ sections, and 3 mile sections. The figure shows fairly similar probabilities of drilling for each type of section for years up until the 1970's. However, starting in about 1980, drilling probabilities on 16/36 sections and sections 3 miles away began to diverge from the $1-\sqrt{5}$ sections.[27] This suggests that policies in the 1970's like NEPA are a major cause of the spatial drilling patterns we see today.

Similarly, I examine wildcat drilling patterns over time. In Figure 7, I show two overlapping histograms of the number of wildcat wells drilled on 16/36 sections as well as on sections which are one mile from 16/36 sections, binned into 5-year periods. The number above the bars is the ratio of total number of wildcat wells drilled on sections one mile to 16/36 sections with the number drilled on 16/36 sections. If policies on federal and state land were identical, we would expect a ratio of four to one, because there are typically four one-mile sections for every 16/36 section. However I find that the ratio has decreased over time. For each five year period before 1980, the ratio tends to be above 4, although there are some low-volume periods with ratios less than 4. For the period after 1980, the ratio is always less than or equal to 3. For example, from 2005 to 2010 the ratio was only 1.5. This changing ratio suggests that shifting policies have made federal land less desirable over time.

[26] One reason for greater heterogeneity in firms on and near state land is that leases on state land in 16/36 sections are typically 1 square mile whereas leases on federal land are often larger than 1 square mile. Another reason is that some firms may specialize in operating on state land while others specialize in operating on federal land.

[27] The online appendix includes the regression analog of Figure 6.

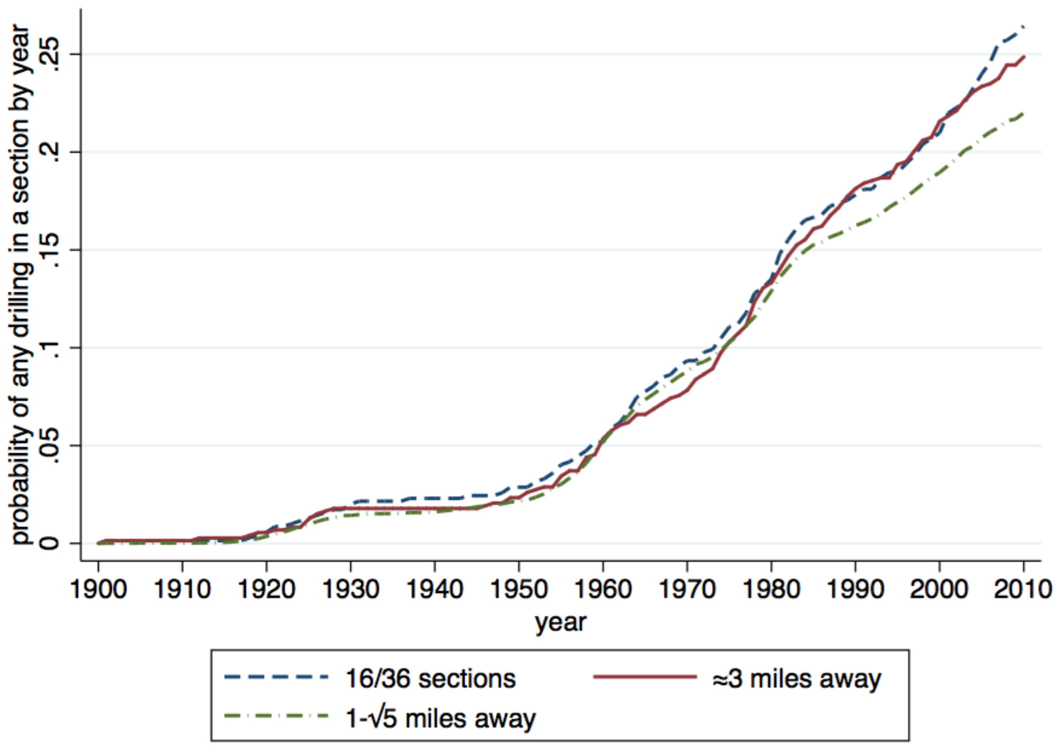

FIGURE 6. ROLLOUT OF DRILLING ON 16/36 SECTIONS, SECTIONS ≈3 MILES AWAY, AND SECTIONS THAT ARE BETWEEN 1 AND $\sqrt{5}$ MILES AWAY. THE VERTICAL AXIS MEASURES THE FRACTION OF SECTIONS IN EACH CATEGORY THAT HAVE BEEN DRILLED BY THAT DATE.

V. Conclusion

In this paper I examine the spillover effects of policies on oil and gas outcomes, showing how policies on one plot of land affect drilling and production outcomes on nearby land. I show why a policy that lowers costs for drilling on one plot of land can either increase or decrease drilling and production on nearby land. Using a natural experiment with exogenously assigned ownership, I find that proximity to state land lowers drilling on federal land—evidence of the substitution effect. I also find that federal wells that are closer to state land have on average lower productivity than federal wells far from state land—evidence of the total expected cost effect.

One insight of this paper is that spillover effects of policy can be far reaching. With this natural experiment, I identify that spillover effects reach at least $\sqrt{5}$ miles away. However, the fact that oil and gas productivity seems to be correlated up to

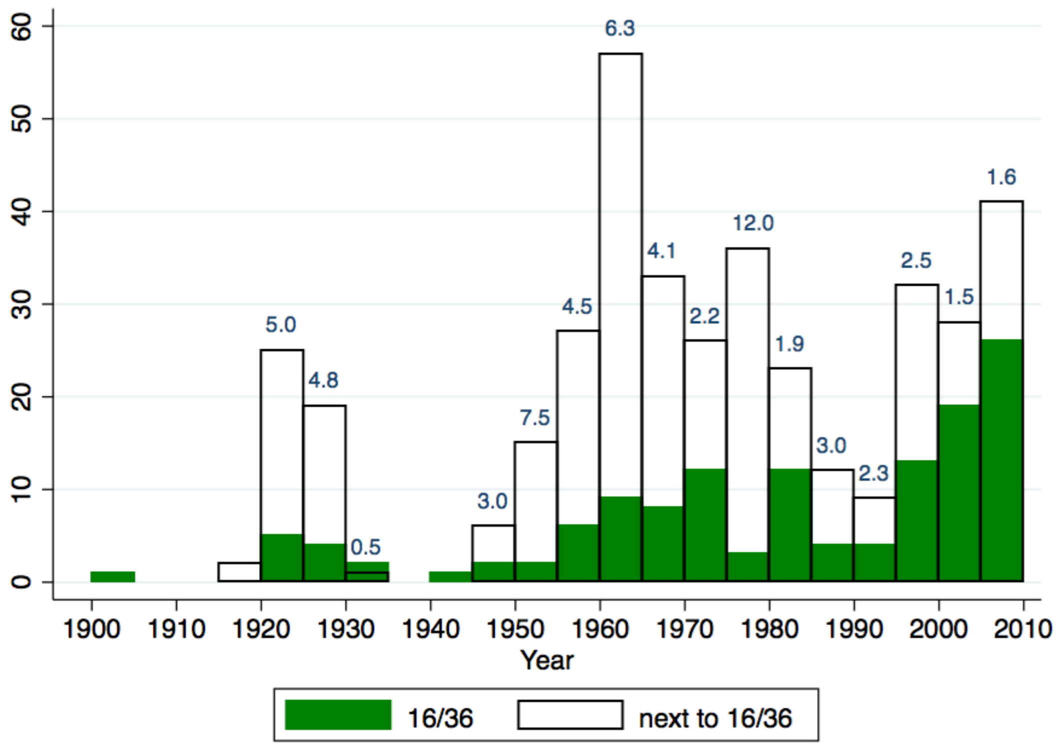

Figure 7. Number of wildcat wells drilled on 16/36 sections (green bars) and on sections that are adjacent to 16/36 sections (transparent bars), by five-year increment. The number above the bar is the ratio of the height of the white bar to the height of the green bar.

20 miles away suggests that spillover effects may extend further (Figure 4).

Another insight of this paper is that evaluating policies by measuring well-level production may be biased if it does not account for what land is selected for drilling. In this paper, I find that wells on state land produce less on average than wells on federal land. While a naïve analysis may conclude that this is driven by state policies that decrease well productivity, my results suggest a different mechanism—that lower productivity land is more likely to get drilled if it is assigned to state ownership.

While this paper focuses on Wyoming, it is likely that similar spillover effects exist elsewhere. Using data from a number of other states, I find that the number of wells on lands designated for state ownership through the Land Ordinance of 1785 is significantly higher than would be predicted if well location was uncorrelated with ownership.[28] The differences in drilling outcomes suggest that federal and state policies differ significantly in these locations, and that therefore there may be significant spillover effects of policies onto neighboring land.

While this paper examines the net effect of state ownership policy spillovers onto federal land, further research should identify the policy or policies that cause these spillovers. For example, low rates of drilling on on federal land that is close to state land may be caused by environmental restrictions, delays, longer primary terms, or all three. Other policies, such as royalty rates, may have additional spillover effects.[29] Additional data such as drilling permit dates and lease expiration dates may be used to disentangle the effects of these various policies.

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[28] I compile data on the location of top holes of wells in Montana, Colorado, Utah, and New Mexico. Like Wyoming, these are states where the the original state land assignment from the Land Ordinance of 1785 has remained relatively robust, where there is significant oil and gas drilling, and where there is high-quality oil and gas data. In Colorado and Montana where sections 16 and 36 were also assigned to state ownership, I find that 6.3% and 6.0% of wells are on 16/36 sections, compared to a predicted fraction of 5.6%. In New Mexico and Utah, where sections 2, 16, 32, and 36 were allocated to state ownership, I find that 11.9% and 12.4% of wells are on these sections, compared to a predicted fraction of 11.1%. And in Wyoming, the fraction of wells on 16/36 sections is 6.5%, compared to a predicted fraction 5.6%. Treating each of these 5 states as an observation, I reject at the 5% level that the predicted fraction of wells on lands allocated for state ownership is equal to the observed fraction.

[29] For example, one anonymous referee pointed out that if federal leases have higher fixed costs but lower royalty rates, then the optimal strategy is to first drill on state land where the fixed costs are low, and then once it learns more about the most efficient way to drill and produce, it then drills and produces from federal land where it capitalizes on the lower royalty rate.

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