Permits as Real Options: Evidence and Implications for Regulation

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Abstract

We identify a new channel for regulatory leakage: the "permitting channel". In many settings, permits lock in the regulatory regime at approval, allowing firms to cheaply acquire the option to invest under current rules. Unlike the Green Paradox, this channel operates without accelerating physical investment and pollution. We develop a dynamic discrete choice framework in which firms can use real options to avoid anticipated regulation. We estimate the framework using quasi-experimental evidence on Colorado's 2019 oil and gas reforms, where permits surged before regulation while drilling remained flat. We find that removing the permitting channel reduces pollution despite amplifying anticipatory investment.

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1 Introduction

A central concern in environmental and regulatory economics is that firms will accelerate investment in anticipation of future regulation. This 'Green Paradox' prediction typically relies on the assumption that firms can only avoid future regulation by accelerating the investment itself.[1] In many settings, however, firms can access real options (Dixit and Pindyck, 1994) — permits, leases, or licenses that grant the right, but not the obligation, to invest under current rules — that can partially shield them from new regulation. These instruments separate regulatory lock-in from physical investment. Despite their prevalence across regulatory settings, little is known about how such options alter anticipatory behavior.

In this paper, we argue that when firms hold real options that can shield them from regulation, their anticipatory response is fundamentally different. Here, rather than moving forward investment, firms can secure favorable regulatory treatment by acquiring a relatively low-cost permit. The result is a 'mirror image' of the standard empirical prediction: permits surge before regulation takes effect, but the investment (and resultant pollution) they authorize occurs *afterwards*. Moreover, because options are cheap relative to the investment they authorize, this channel can amplify anticipatory effects beyond what an investment-only model would predict.

Our main research question is: how much does the permitting channel erode the effectiveness of regulation? Focusing on Colorado's sweeping 2019 oil and gas regulatory changes, we answer this question in three steps.[2] We begin by providing quasi-experimental evidence consistent with permits serving as real options. Next, based on this evidence, we estimate

[1] We define the 'Green Paradox' — consistent with the previous literature — as intertemporal substitution of pollution caused by anticipated future increases in regulatory stringency. The Green Paradox was originally conceived as about extraction acceleration [Sinn, 2008]. However, the term has broadened to encompass intertemporal leakage through the investment margin [Kellogg, 2024] (since typically production from existing wells follows a decline curve that does not respond to prices [Anderson et al., 2018] and so responses are likely primarily on the extensive margin of investment) and commodity storage [Lemoine, 2017]. What ties these examples together is that anticipated regulation shifts the regulated activity and pollution forward in time (see [Jensen et al., 2015] for a survey).

[2] The regulation focused on 'setback' provisions which limit new drilling near residential areas. The motivation for these provisions is that oil and gas operations emit local pollutants whose concentrations and health consequences decline sharply with distance from the well. Therefore, proximity to drilling is a first-order determinant of pollution exposure.

a dynamic discrete choice model of permit acquisition and drilling.[3] Finally, we evaluate counterfactual policy designs and show that removing the permitting channel *improves* health outcomes despite amplifying the Green Paradox.

Although our focus is on oil and gas in Colorado, the economic channel is much broader. It could potentially operate in any setting where firms hold real options that can shield them from regulation and have advance notice of the change. We document the permitting channel in several of these settings in more detail later in the paper, including California's setback regulations [CalGEM, 2024], federal oil and gas permitting [Biden for President Campaign, 2019], New York City housing [NYU Furman Center, 2015], and Chinese coal plant approvals [Centre for Research on Energy and Clean Air, 2023].

Colorado's 2019 oil and gas regulatory reform is an ideal setting to study the permitting channel. In 2018, a ballot initiative proposed 2,500-foot setbacks from occupied buildings (and "vulnerable areas" such as waterways and reservoirs), which would have amounted to an effective ban on new drilling in the state. Although the referendum failed, a newly elected governor implemented a version of the stricter rules in early 2019, with permits approved before implementation exempt from the new requirements.

Using a difference-in-differences design comparing county-play-level outcomes in Colorado to Texas, which isolates Colorado-specific anticipatory responses from aggregate shocks to oil and gas markets, we document three observations.[4] First, the anticipated regulation triggers a surge in permitting (with approvals peaking at over 100% above the control group in the quarter before regulation) and a post-regulation permit overhang as firms stockpile permits under the existing rules. Second, investment does not increase prior to regulation, consistent with permits serving as real options. Third, the permit overhang increases pollution exposure post-regulation. Specifically, using a cross-sectional difference-in-differences, we find that non-grandfathered wells are significantly less likely to be drilled near buildings and have substantially lower neurotoxicity health effects than wells drilled under grandfathered permits.

[3] We use the terms 'drilling' and 'investment' interchangeably throughout.

[4] A play is a geological formation targeted for drilling.

We next develop a dynamic discrete choice model where firms separately time permit acquisition and drilling to evaluate counterfactual policy designs. Firms own drilling prospects that differ in proximity to buildings and receive idiosyncratic shocks to the value of their prospects each period. They anticipate regulation will occur at a specific period in the future (here, Q1 2019) with a given probability. In our application, we model this anticipated regulation as comprising a ban on drilling — consistent with the institutional details — plus ongoing increases in compliance costs for all existing wells.

Permits obtained before regulation are grandfathered from the new drilling ban, but not the increases in ongoing compliance costs. Therefore firms can respond to anticipated regulation in several ways: firms can accelerate drilling, acquire a permit and wait for uncertainty to resolve, or do nothing and face the new regime. Overall, the model embeds three key effects. The first two are documented in the previous literature — the 'Green Paradox' effect where they invest sooner, and a disinvestment effect from increases in compliance costs to existing wells. The third is the effect of the permitting channel, where firms simply acquire permits but do not change when they invest.

We estimate the model via simulated method of moments. We leverage the event study and cross-sectional difference-in-differences estimates for identification. Pre-regulation permitting dynamics identify firms' beliefs about the probability of regulation. The cross-sectional difference in drilling locations post-regulation identifies the realized regulatory costs.

We use the estimated model to evaluate counterfactual policy designs, starting from the implemented regulation.[5] First, we eliminate grandfathering so that all drilling faces new requirements regardless of when the permit was approved. Firms can no longer avoid regulation through cheap permits and must instead accelerate costly drilling. Therefore, although this causes intertemporal leakage/a Green Paradox, it actually reduces pollution because fewer firms respond. Health-weighted drilling near homes falls by 27%. Second, we remove anticipation, simulating a surprise regulation, which eliminates the pre-regulation investment spike. This yields an additional 13 percentage point reduction in pollution, for a total

[5]Grandfathering is common because exempting incumbents from new requirements is often politically necessary to pass stricter standards [Serkin and Vandenbergh, 2018, Nash and Revesz, 2007].

cumulative reduction of 40%.

1.1 Related Literature and Contributions

Our first contribution is to identify and quantify a new channel for regulatory leakage, the permitting channel. Empirical tests of anticipatory behavior typically measure whether physical economic activity accelerates before regulation takes effect. Examples include fossil fuel markets [Di Maria et al., 2014, Lemoine, 2017, Kellogg, 2024], freight truck purchases [Rittenhouse and Zaragoza-Watkins, 2018, Fu et al., 2024], fishing [McDermott et al., 2019]. By contrast, the permitting channel operates without accelerating investment and is therefore invisible in these tests. Furthermore, the prior literature has typically considered settings where the regulated activity itself is the instrument of lock-in. For example, firms must fish [McDermott et al., 2019], operate a pollution source [Nash and Revesz, 2007], or purchase a vehicle [Rittenhouse and Zaragoza-Watkins, 2018] to secure favorable treatment. The permitting channel is fundamentally different because permits separate lock-in from investment: firms can secure grandfathered status cheaply, without accelerating the costly activity.

Our second contribution is to provide quasi-experimental evidence on the permitting channel and estimate a structural model that embeds it. We build on the literature on institutional frictions in oil and gas and energy markets [Herrnstadt et al., 2024, Muehlenbachs et al., 2015, Johnston et al., 2023, Lange and Redlinger, 2019], and on dynamic models of firm behavior under uncertainty [Gowrisankaran et al., 2025, Kellogg, 2014]. We extend these models by embedding the permitting channel, allowing firms to separately time permit acquisition and investment. This distinction is central: existing models treat the investment decision as a single margin, whereas in our framework the permit and the drilling decision are separate choices with different costs and payoffs.

Our third contribution is to quantify the costs of the permitting channel for regulatory effectiveness. We evaluate counterfactual policy designs, contributing to structural models of environmental and energy regulation [Ryan, 2012, Fowlie, 2010, Jha, 2019, Sileo, 2022, Leisten and Vreugdenhil, 2026]. Grandfathered permits allow drilling in the locations the regulation was specifically designed to protect, generating health costs that alternative de-

signs would avoid. We quantify these health consequences, adding to work on externalities from oil and gas development [Muehlenbachs et al., 2015].

2 Background and Data

2.1 Institutional background

In Colorado, operators must obtain a non-tradeable drilling permit from the Colorado Oil and Gas Conservation Commission (COGCC) before drilling a new well. Permits remain valid for two years [Colorado Oil and Gas Conservation Commission, 2019b]; if drilling does not commence within this window, the permit expires. The key institutional feature for our analysis is that permits partially lock in the regulatory regime at approval. When new regulations take effect, they apply only to permits issued afterward; wells drilled under previously approved permits are grandfathered. For operators, grandfathering transforms permits into options: by obtaining a permit before anticipated regulation, a firm secures the right—but not the obligation—to drill in a specific location under favorable conditions for up to two years.[6]

Our analysis covers three periods and Figure 1 summarizes the timeline. The *pre-period* (2017) provides a baseline when Colorado's regulatory landscape was relatively stable. The *anticipation period* (2018) began when firms learned of potential regulatory tightening through a referendum which would take place in Q4 2018.[7] The proposed legislation is arguably best described as a ban on new drilling. Specifically, the proposed regulation involved 2,500-foot 'setbacks' (i.e., restrictions on drilling within 2,500 feet) from occupied buildings (and "vulnerable areas" such as waterways and reservoirs). A COGCC impact assessment estimated that 85% of non-federal land in Colorado would be inaccessible under the proposed setbacks, rising to 94% in the top five producing counties [Colorado Oil and Gas Conservation Commission, 2018]. In our data, 96% of wells drilled in 2017 were on non-federal land. We date the anticipation period from Q1 2018, when the ballot initiative was initially filed [Colorado

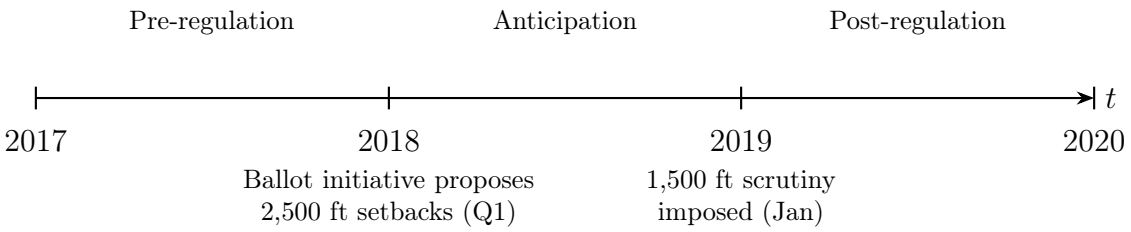
[6]The cost of this option is low, consisting primarily of application fees and engineering documentation, while the cost of exercising the option (drilling) runs into millions of dollars.

[7]At the same time as the referendum there was also an election for the governor and legislature.

Secretary of State, 2018].

The *regulation period* spans 2019. Although the referendum failed, voters elected a Democratic governor and legislative majority in Q4 2018. As a consequence, the new administration implemented a weaker version of the regulation anyway. Specifically, in January 2019 the new governor appointed an oil and gas regulator who immediately imposed additional scrutiny on permit applications for wells within 1,500 feet of occupied buildings [Finley, 2019]. We therefore date the regulation period from Q1 2019.[8] We end the sample in Q4 2019 because 2020 coincides with Covid, making clean identification difficult in this period.

Figure 1: Institutional timeline: Colorado oil and gas reform.



Note: Permits approved before 2019 are grandfathered and exempt from the new requirements.

2.2 Data

We combine oil and gas permit and drilling data with detailed spatial information on nearby buildings and populations. Table 1 reports descriptive statistics.

Permits and Wells We obtain data from Enverus covering the complete universe of drilling permits and subsequent well development in Colorado and Texas. Our data distinguish between permits (approved applications to drill) and wells (permits that were exercised). Table 1 reports 8,237 Colorado permits from Q1 2017 to Q4 2019, of which 4,681 resulted in drilled wells. Not all permits lead to drilling: some expire unused, reflecting the option value that permits provide. Production data are available only for drilled wells. We exclude permits and wells (8% and 6%, respectively) in five counties—Boulder, Adams,

[8]These administrative criteria were codified in the Director's Draft Objective Criteria after Senate Bill 19-181 was signed in April 2019 [Colorado Oil and Gas Conservation Commission, 2019a] and the permanent provisions took effect in January 2021. We focus on the interim stringency imposed by the regulator in 2019.

Larimer, Arapahoe, and La Plata—that implemented or attempted to implement additional local controls in 2019. We further restrict the sample to horizontal and directional wells, which account for 98% of permits, to maintain comparability across observations.

Buildings We construct the buildings dataset by combining multiple sources. We start with the Microsoft US Building Footprints Project, which provides millions of building footprints across Colorado and Texas, then match these to parcel-level data from Regrid to classify buildings by land use. We identify residential buildings using Land-Based Classification Standards (LBCS) codes. Appendix B provides details on the matching procedure; Appendix Figure 6 illustrates the classification for a sample area.

Health risk by distance. We obtain health risk measures from the Human Health Risk Assessment, which was commissioned by the Colorado Department of Public Health and Environment [ICF, 2019]. This engineering study estimates acute non-cancer hazard indices for populations living near oil and gas production sites. We extract hazard indices by distance for four critical-effect groups from Table E-31 of the report: hematological, neurotoxicity, respiratory, and systemic[9]. Hematological and neurotoxicity indices are an order of magnitude larger than respiratory and systemic indices at all distances (Appendix Figure 8), so we focus on these two measures.

These indexes quantify the health effects of a nearby well on a single individual. However, wells can potentially affect multiple people if they are drilled in a populated area. As a result, we construct a well-level health risk measure using a concentric ring analysis. We count the number of residential buildings within 16 distance bands around each permitted well, using coordinates from the permit data, and weight each building by the hazard index at its distance (Appendix B).[10]

[9]Hematological indices measure effects on blood and blood-forming organs; neurotoxicity indices measure effects on the nervous system.

[10]We normalize each building to have one individual living inside it. However, all of our results are reported in percentage changes in aggregated health indexes, and so the level of this normalization does not affect our results since it cancels out in these percentage measures.

Table 1: Descriptive Statistics: Oil and Gas Wells and Sample Composition

	Summary Statistics				Sample Composition	
Variable	**N**	**Mean**	**P10**	**P90**	**Category**	**Count (%)**
Panel A: Production (First 3 Years, Drilled Wells)					*Geographic Distribution*	
Oil (thousand bbl) - CO	4,681	97.9	0.5	209.2	Total Permits	33,471 (100%)
Oil (thousand bbl) - TX	22,312	188.8	0.0	364.0	Colorado	8,237 (24.6%)
Gas (million mcf) - CO	4,681	682.0	148.6	1293.6	Texas	25,234 (75.4%)
Gas (million mcf) - TX	22,312	843.4	17.4	1859.0		
Panel B: Spatial & Health (Permits)					Wells Drilled	26,993 (100%)
Distance to Building (mi) - CO	8,237	2.1	0.2	5.2	Colorado	4,681 (17.3%)
Distance to Building (mi) - TX	25,234	5.0	0.4	13.8	Texas	22,312 (82.7%)
Hematological Index - CO	8,237	0.3	0.0	1.1		
Hematological Index - TX	25,234	0.1	0.0	0.4		
Neurotoxicity Index - CO	8,237	0.1	0.0	0.2		
Neurotoxicity Index - TX	25,234	0.0	0.0	0.1		

Notes: P10 and P90 denote the 10th and 90th percentiles. Health indices are acute non-cancer hazard indices from ICF [2019].

3 Quasi-Experimental Evidence of the Permitting Channel

We document three observations about the effects of the regulation on permitting, investment, and the types of wells drilled.

Observation 1: Anticipated regulation triggers a permitting surge and a post-regulation permit overhang.

We use an event study to estimate the effects of the policy on permitting and drilling. Our empirical strategy compares county-play-level outcomes in Colorado, where regulation was introduced, to control groups in Texas, where it was not.[11]

Concretely, we estimate Poisson specifications in the following form:

$$y_{it} = \exp\left(\left(\sum_{j=-L}^{R} \beta_j D_{i,t+j}\right) + \alpha_i + \eta_t + X'_{it}\delta\right)\epsilon_{it} \tag{1}$$

[11]The Texas controls serve to net out global oil and gas price fluctuations and other aggregate effects. Furthermore, oil and gas prices are relatively stable during our sample period with WTI crude averaging $55 per barrel in 2017–2019 with limited volatility.

The dependent variable y_{it} is measured at the quarterly (t) county-play (i) level. We run separate regressions for two outcomes: the count of approved permits and the count of drilled (i.e. 'spudded') wells. The specification includes group-level fixed effects α_i, quarterly fixed effects η_t. We also include quadratic time-varying controls for oil and gas revenue (the average volume of oil and gas per well in county-play i multiplied by the prices) in X_{it}. The coefficients β_j therefore capture log deviations in activity relative to Texas around the announcement date ($t = 0$). We cluster standard errors at the county-play level. We also estimate a difference-in-difference specification by aggregating time into the three periods defined in Section 2.1: pre-announcement, anticipation, and post-regulation.

Table 2: Difference-in-difference results

	Permit Application	Permit Overhang	Drilling
Anticipation	0.26	0.05	-0.16
	(0.11)	(0.10)	(0.06)
Interim	-0.65	0.28	-0.39
	(0.24)	(0.12)	(0.11)
Observations	3770	2990	3627
Pseudo R^2	0.91	0.49	0.97
Quadratic oil/gas controls	Yes	Yes	Yes

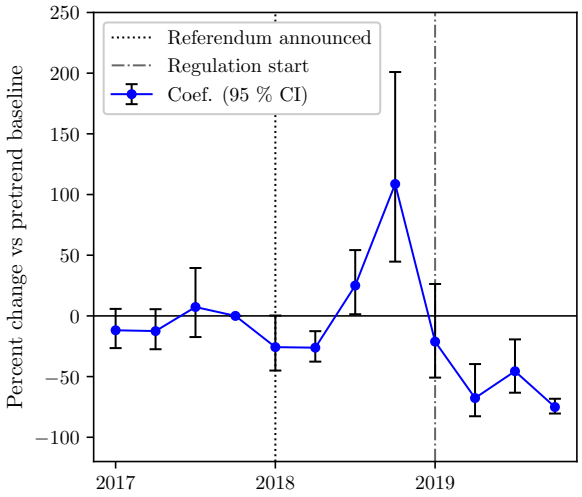
Note: Poisson pseudo-maximum likelihood estimates. Coefficients are log changes relative to the pre-period (2017). Standard errors clustered at the county-play level in parentheses. Controls include quarter fixed effects, county-play fixed effects, and log oil and gas revenue.

Figure 2 presents the event study estimates and Table 2 reports the difference-in-difference results. In the pre-announcement period, both approvals and drilling show parallel trends between treated and control groups.

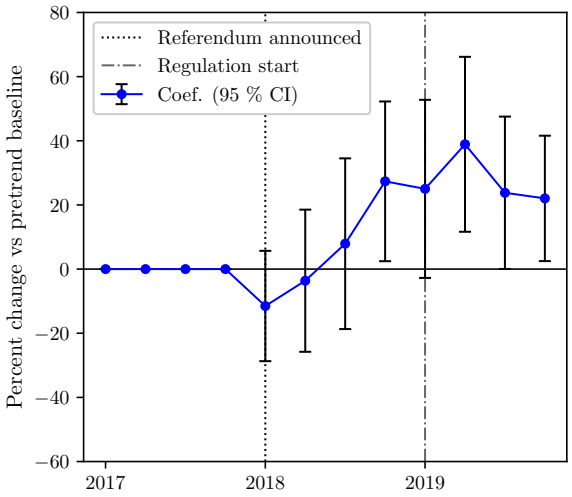
After the ballot initiative filing (Q1 2018), firms raced to secure permits, with approvals peaking at over 100% above the control group in Q4 2018 (Figure 2a). The difference-in-difference results in Table 2 confirm this pattern. Firms directly communicated their intentions to stockpile permits. For example, one firm said that they "anticipat[e] having more than three years of drilling inventory permitted and "ready to go" if the measure

Figure 2: Effects of the regulation on permitting and drilling

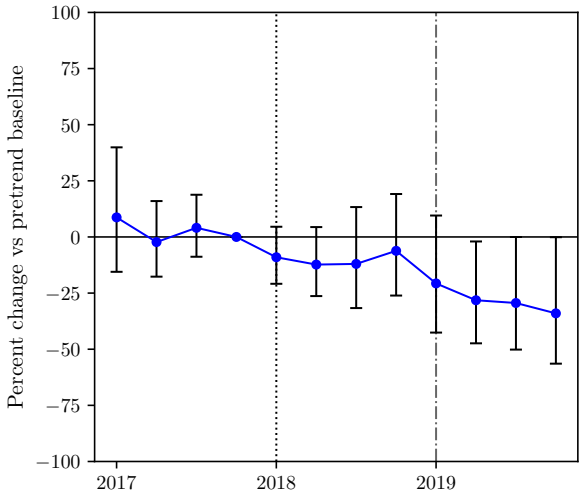
(a) Effect on permit approvals



(b) Effect on permit overhang



(c) Effect on drilling new wells



Note: Event study estimates from Poisson regression at the county-play-quarter level. The omitted period is 2017Q4. Vertical dashed lines mark the start of anticipation (2018Q1) and regulation (2019Q1). Shaded region indicates the post-regulation period. Control group is Texas county-plays. Panel (b) measures the permit overhang as the share of outstanding permits approved during the anticipation period (2018); each permit is tracked from approval until exercise or expiration. 95% confidence intervals shown.

passes" [Traywick, 2020].

After the regulation takes effect, Figure 2a shows a drop in permitting of more than 50%. Figure 2b shows the *permit overhang* — the share of outstanding permits that were approved during the anticipation period — which remains elevated throughout 2019. We construct

the overhang by tracking each permit from its approval date until it is either exercised or expires, then measuring the fraction approved in 2018 among all permits outstanding in each quarter.

Observation 2: Investment does not increase during anticipation.

Using the same specification, Figure 2c shows that drilling does not increase during the anticipation period.[12] Table 2 confirms the absence of a drilling response. The contrast with Observation 1 is sharp: while firms rush to secure permits, they do not accelerate drilling. This divergence is consistent with permits serving as options — firms secure the right to drill under existing regulations at low cost, without committing the capital for a well they may not have drilled otherwise.

After the regulation takes effect, Figure 2c shows a corresponding decrease in drilling. Note that grandfathered permits can affect not only the *quantity* of wells drilled but also the *type*: firms with grandfathered permits may drill closer to residential areas than firms obtaining permits under the new regulation. We turn to this question in Observation 3.

Observation 3: Grandfathered permits produce wells closer to residential areas with higher health risks.

We use a cross-sectional difference-in-difference to estimate how the permitting channel affects the types of wells drilled. We focus on wells drilled after the regulation takes effect (2019), when both grandfathered permits from the anticipation period and permits awarded under the new regulation are in use. Denote s as the state (Colorado or Texas) and r as the regime under which the permit was awarded (pre- or post-regulation). We recover the effect β_1 from the following regression:

$$y_{ir} = \beta_0 + \beta_1 D_{s(i)=\text{Colorado},r=\text{Post}} + \alpha_{Texas} + \eta_{Post} + Z_i'\delta + \epsilon_{it} \tag{2}$$

[12]The point estimate is slightly negative, though not significant at the 95% level. This is consistent with a small disinvestment effect, since permits are only a partial shield against regulatory costs.

Table 3: Comparing permits approved pre vs post-regulation for wells drilled post-regulation

	(1)	(2)	(3)
Close to buildings			
Estimate	-0.13	-0.13	-0.13
	(0.017)	(0.017)	(0.017)
Percent change vs. mean	-33.51	-34.45	-34.83
Hematological health effects			
Estimate	-0.11	-0.11	-0.11
	(0.021)	(0.021)	(0.021)
Percent change vs. mean	-22.48	-23.63	-24.08
Neurotoxicity health effects			
Estimate	-0.024	-0.025	-0.026
	(0.0047)	(0.0047)	(0.0047)
Percent change vs. mean	-22.91	-24.07	-24.53
Hydrocarbon production (thousand BOE)			
Estimate	4.0	5.3	5.4
	(7.4)	(7.3)	(7.3)
Percent change vs. mean	3.72	5.02	5.09
Observations	8967	8967	8967
County controls	Yes	Yes	Yes
Basin controls	No	Yes	Yes
Play controls	No	No	Yes

Note: Cross-sectional difference-in-difference regression with Texas wells as control group. Sample restricted to wells where drilling (spud date) occurs during the post-regulation period, when both grandfathered permits and permits under the new regulation were in operation. Each estimate row is a separate regression of the outcome on an indicator for whether the permit was approved before (pre-2019) or after regulation. 'Close to buildings' indicates the well is within 1,500 feet of a building. Hydrocarbon production is measured in barrels of oil equivalent (BOE), which converts gas into oil-equivalent units using the standard energy-content ratio (1 BOE $\approx$ 5.8 MCF of gas). Columns (1)–(3) use increasingly fine geographic controls; column (3) matches the group definition in Table 2.

Here, α_{Texas} is a fixed effect for wells located in Texas and η_{Post} is a fixed effect for permits awarded under the post-regulation regime. We estimate three specifications with increasingly fine geographical controls Z_i'; our preferred specification controls for geography at the county-

play level, consistent with the group definition in the event study regressions.

Table 3 reports the results. Each row is a separate regression; columns use incrementally finer geographical controls. We convert each estimate into a percentage change relative to the pre-regulation baseline.

The first outcome, close to buildings, indicates whether the well is within 1,500 feet of a residential building, matching the 2019 regulatory threshold (Section 2.1).[13] We find that wells permitted after the regulation are about 35% less likely to be drilled near buildings. The next two outcomes map distances from buildings into hematological and neurotoxicity health effects using hazard indices from ICF [2019] (Section 2.2). Non-grandfathered wells show 24% lower hematological effects and 25% lower neurotoxicity effects, indicating that the permit overhang from the anticipation period has measurable health consequences. Hydrocarbon production, by contrast, shows no significant difference between grandfathered and non-grandfathered wells (Table 3).

4 A model of regulation with the permitting channel

The descriptive evidence in Section 3 documents how anticipation and grandfathering affect permitting and drilling. However, it cannot evaluate counterfactual regulatory designs, such as eliminating grandfathering, because firms' drilling and permitting decisions would change endogenously under different rules. Therefore, we develop a dynamic discrete choice model of the industry.

Overall, permits in our model function as real options: by obtaining a permit, a firm locks in the right to drill in a specific location under current rules. Facing expected regulation, firms choose among three responses: drill (invest) immediately, obtain a permit to preserve the option to drill later, or wait without a permit.

Intuitively, the option value of a permit comes from the choice of when to time the irreversible drilling investment. Firms wait for favorable drilling conditions before committing capital

[13] Raw mean distance is less informative because it is driven by the large mass of wells far from any building. The 1,500-foot indicator captures the policy-relevant margin.

[Kellogg, 2014], and the permit preserves this choice even after regulation is introduced. Note that firms perceive a probability of regulation, and although this affects how *valuable* the option is, regulatory uncertainty does not create the optionality; rather, the optionality comes from uncertainty in current and future drilling conditions.

Recall from Section 2.1 that firms anticipated an effective ban on drilling near buildings, but the realized regulation imposed moderate additional costs on close wells rather than prohibiting them. As a result, we allow anticipated and realized regulatory costs to differ in the model.

4.1 Environment

Time is discrete with one period equal to one quarter, and agents discount future payoffs at a rate β. Agents are firms who own drilling prospects (potential wells). Each prospect i is characterized by its proximity type $d_i \in \{\text{far}, \text{close}\}$, indicating distance to occupied buildings. All prospects share a common ex-ante expected net present value of production q; proximity type is the only source of prospect-level heterogeneity.[14] Oil wells produce along a fixed decline curve once drilled, so the firm's decision is when to drill, not how much to extract [Anderson et al., 2018, Kellogg, 2024]. We normalize the stock of prospects to 1. Because all quantities are reported in shares or percentage changes, this normalization is innocuous.

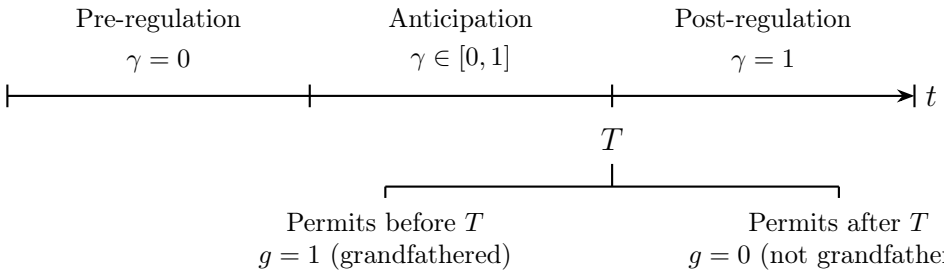
Regulatory regimes and permits. Let γ denote firms' perceived probability that regulation arrives at $t = T$. The model features three regimes described in Section 2.1: the pre-regulation period, the anticipation period, and the post-regulation period. During the pre-regulation period, firms do not expect regulation ($\gamma = 0$). During the anticipation period, firms hold a constant belief $\gamma \in [0, 1]$ that the regulation will arrive. During the

[14]The model still allows for differences in profitability across prospects through the idiosyncratic shock. Although we could extend the model to capture additional observable heterogeneity in q, we choose to not do this to keep the model parsimonious and because it is unlikely to have a first-order effect on the results. Specificially, a key concern with a common q would be if the regulation indirectly affected hydrocarbon quantity through correlation with distance from buildings. However, recall that we find no significant differential effect in production between grandfathered and non-grandfathered permits in Table 3, suggesting this is not a concern. Furthermore, oil and gas prices were relatively stable during our sample period between 2017 and 2019, supporting the assumption of constant q across time.

post-regulation period ($t \geq T$), the regulation is in effect ($\gamma = 1$). We omit time subscripts on γ because, from the agents' perspective, this belief is held constant within each regime. However, from the econometrician's perspective, in estimation we can compute how these expectations change period by period within regimes. Furthermore, in our model, the regulation firms anticipate may differ from the regulation actually implemented, and so anticipated and realized regulatory costs need not coincide.

If a firm chooses to permit a prospect, the permit has state (τ, g), where τ is the remaining permit maturity in quarters and g is grandfathering status. New permits are issued with full maturity $\tau_{\max}$ (two years of validity) and age by one quarter each period. Permits obtained before T are grandfathered ($g = 1$) and are exempt from additional permit costs defined below; permits obtained after T have $g = 0$. Figure 3 summarizes this structure.

Figure 3: Regulatory timeline and grandfathering.



Note: The timeline shows three regulatory regimes. During pre-regulation, firms do not expect regulation ($\gamma = 0$). During anticipation, firms assign probability $\gamma \in (0, 1)$ to regulation arriving at T. Post-regulation, the regulatory regime is in effect ($\gamma = 1$). Permits obtained before T are grandfathered ($g = 1$) and exempt from additional close-well costs.

Within-period timing. At the start of each period, firms with unpermitted prospects choose whether to obtain a permit or wait. Firms choosing to permit immediately decide whether to drill or let the permit age, so permitting and drilling can occur in the same period. Firms holding permits from previous periods choose whether to drill or let the permit age. Permits that are not exercised age by one quarter; at $\tau = 0$ an unexercised permit expires and the prospect reverts to an unpermitted status.

Payoffs. Let $\pi_{i,r}$ denote the flow payoff from drilling prospect i under the regulatory regime $r \in \{\text{pre}, \text{post}\}$, and let $c_{i,r}$ denote the cost of obtaining a permit. Note that the drilling

payoff depends on the common production value q. Furthermore, both payoffs and permit costs vary across regimes, reflecting how regulation affects drilling profitability and the costs of obtaining permits. For example, regulation may impose additional permit costs for wells close to buildings, with a complete ban captured by $c_{i,\text{post}} = \infty$. Similarly, regulation may affect drilling payoffs $\pi_{i,r}$ if it increases extraction costs or imposes ongoing operational requirements, which may not be shielded by a grandfathered permit. Table 4(a) reports the specific functional forms.

Payoffs are subject to i.i.d. type-1 extreme value shocks, with scale σ_{permit} for permitting decisions and σ_{drill} for drilling decisions, yielding standard logit choice probabilities.

4.2 Value Functions and Choices

Pre and post-regulation regimes. We first characterize value functions under a fixed regulatory regime $r \in \{\text{pre}, \text{post}\}$. In this setting, grandfathering is irrelevant (all firms share the same status). We suppress the grandfathering state g from the value functions throughout since g is determined by the timing of permit acquisition and is implicit in the prospect index i. Let $W_{i,r}$ denote the value of an unpermitted prospect i under regime r. The firm chooses between permitting and waiting.

$$W_{i,r} = \mathbb{E}_\varepsilon \max \Big\{ \underbrace{-c_{i,r} + P_{i,r,\tau_{\max}} + \sigma_{\text{permit}}\varepsilon_{i,1}}_{\text{permit}}, \quad \underbrace{\beta W_{i,r} + \sigma_{\text{permit}}\varepsilon_{i,2}}_{\text{wait}} \Big\} \tag{3}$$

where $\tau_{\max} = 7$ is the initial permit maturity, $c_{i,r}$ is the permit cost (which depends on proximity type d_i and regime r as defined in equation 4a), β is the quarterly discount factor, and $P_{i,r,\tau}$ is the value of holding a permit with maturity τ.[15] For a permitted prospect with maturity $\tau > 0$:

$$P_{i,r,\tau} = \mathbb{E}_\varepsilon \max \Big\{ \underbrace{\pi_{i,r} + \sigma_{\text{drill}}\varepsilon_{i,3}}_{\text{drill}}, \quad \underbrace{\beta P_{i,r,\tau-1} + \sigma_{\text{drill}}\varepsilon_{i,4}}_{\text{let permit age}} \Big\} \tag{4}$$

[15]Maturity $\tau \in \{0, 1, \ldots, 7\}$ indexes the remaining quarters before expiration. A newly issued permit enters at $\tau = 7$ and the firm makes one decision per quarter, so the permit spans 8 quarters (two years) from $\tau = 7$ down to $\tau = 0$.

At $\tau = 0$, waiting causes the permit to expire and the prospect reverts to unpermitted status, so $P_{i,r,0} = \mathbb{E}_\varepsilon \max\{\pi_{i,r} + \sigma_{\text{drill}}\varepsilon_{i,3},\ \beta W_{i,r} + \sigma_{\text{drill}}\varepsilon_{i,4}\}$.

Recall that after permitting, a firm immediately faces a second decision — drill or wait — within the same period. A firm can therefore permit and drill in the same quarter.

Anticipation regime. During the anticipation period, firms believe that regulation arrives with probability γ, and we model value functions recursively using backward induction. All permits obtained before T are grandfathered ($g = 1$) and face only the baseline permit cost c. We denote anticipation value functions with γ as a regime subscript and time t as the final subscript.

Period $t = T - 1$: Uncertainty resolves next period. Continuation values average over two future regimes — $W_{i,\text{pre}}$ if regulation does not arrive, and $\hat{W}_{i,\text{post}}$, computed using anticipated parameters, if it does.[16] Throughout, we use hat notation ($\hat{\cdot}$) for values computed under anticipated parameters and tilde notation ($\tilde{\cdot}$) for values computed under realized parameters. For an unpermitted prospect:

$$W_{i,\gamma,T-1} = \mathbb{E}_\varepsilon \max\Big\{ \underbrace{-c_{i,\text{pre}} + P_{i,\gamma,\tau_{\max},T-1} + \sigma_{\text{permit}}\varepsilon_{i,1}}_{\text{permit}},\quad \underbrace{\beta\big[(1-\gamma)W_{i,\text{pre}} + \gamma\hat{W}_{i,\text{post}}\big] + \sigma_{\text{permit}}\varepsilon_{i,2}}_{\text{wait}} \Big\} \tag{5}$$

For a permitted prospect with $\tau > 0$:

$$P_{i,\gamma,\tau,T-1} = \mathbb{E}_\varepsilon \max\Big\{ \underbrace{(1-\gamma)\pi_{i,\text{pre}} + \gamma\hat{\pi}_{i,\text{post}} + \sigma_{\text{drill}}\varepsilon_{i,3}}_{\text{drill}},\quad \underbrace{\beta\big[(1-\gamma)P_{i,\text{pre},\tau-1} + \gamma\hat{P}_{i,\text{post},\tau-1}\big] + \sigma_{\text{drill}}\varepsilon_{i,4}}_{\text{age}} \Big\} \tag{6}$$

where the hat notation ($\hat{W}_{i,\text{post}}$, $\hat{P}_{i,\text{post},\tau}$, $\hat{\pi}_{i,\text{post}}$) indicates that post-regulation continuation values are computed using anticipated parameters.

Period $t = T - 2$ and earlier: For $t < T - 1$, the recursive structure continues. Continuation

[16] Under our specification with $c_{i,r} = \infty$ in the anticipated post-regulation regime, no new permits are obtained and $\hat{W}_{i,\text{post}} = 0$.

values for waiting and aging point to the next period's value functions rather than mixing over terminal regimes (e.g., the T-2 value functions use the T-1 value functions in the next period). We solve these cases via backwards induction.

At $t \geq T$, regulation is in effect and firms use $\tilde{W}_{i,\text{post}}$ and $\tilde{P}_{i,\text{post},\tau}$ – where the tilde notation indicates these are computed with realized parameters ($\tilde{q}$, $\tilde{c}_{\text{close}}$) – except that grandfathered permits ($g = 1$) remain exempt from additional close-well costs.

4.3 Aggregation and Simulation

Given parameters, we simulate drilling and permitting behavior for each proximity type $d_i \in \{\text{far}, \text{close}\}$ over the 12 quarters, starting from long-run permit stocks under no regulation. Each quarter we compute value functions under the appropriate regime, calculate choice probabilities, and update permit stocks as new permits enter and existing permits age. We weight type-specific outcomes by the share of close prospects to obtain aggregate predictions for drilling rates, permit applications, and permit stocks by vintage. Details are in Appendix A.3.

5 Identification and Estimation

5.1 Overview

Payoff structure. Table 4(a) specifies the drilling payoff $\pi_{i,r}$ and the permit cost $c_{i,r}$ introduced in Section 4 for each regulatory regime. The drilling payoff is net profit from exercising a permit — the lifetime production value q minus drilling cost c_{drill}, minus any regime-specific regulatory costs. Prior to regulation, all prospects share the same payoff $\pi_{i,r} = q - c_{\text{drill}}$ and permit cost c, regardless of their proximity to buildings. During anticipation, firms expected the ballot initiative to effectively ban new permitting, so we set the anticipated permit cost to $c_{i,r} = \infty$.[17] The parameter $\hat{q}$ separately captures the anticipated reduction in production value.

[17]Recall that the 2018 ballot initiative (Proposition 112) proposed 2,500-foot setbacks from occupied buildings (and "vulnerable areas" such as waterways and reservoirs), which would have affected most drilling locations in Colorado [Colorado Secretary of State, 2018].

Table 4: Payoff structure and calibrated parameters

(a) Payoff structure by regime

Regime	Drilling payoff $\pi_{i,r}$	Permit cost $c_{i,r}$
Pre-regulation	$q - c_{\text{drill}}$	c
Post-regulation (anticipated)	$q - c_{\text{drill}} - \hat{q}$	∞
Post-regulation (realized), $g = 0$	$q - c_{\text{drill}} - \tilde{q}$	c (far) or $c + \tilde{c}_{\text{close}}$ (close)
Post-regulation (realized), $g = 1$	$q - c_{\text{drill}} - \tilde{q}$	c

(b) Calibrated parameters

Parameter	Description	Value
β	Quarterly discount factor	0.95
c	Permit cost ($M)	0.003
c_{drill}	Drilling cost ($M)	6.00
q	Lifetime production value ($M)	6.60

Note: Panel (a) shows how drilling payoffs and permit costs vary by regulatory regime and grandfathering status. The anticipated regime reflects firms' expectations during 2018Q3–Q4; the realized regime reflects actual post-2019Q1 conditions. Grandfathered permits ($g = 1$) avoid the close-well surcharge $\tilde{c}_{\text{close}}$. Panel (b) reports externally calibrated parameters; sources are discussed in the text.

The realized regulation was more moderate, imposing additional requirements primarily for wells near occupied buildings.[18] The model captures two forms of regulatory cost. A grandfathered permit protects against costs imposed at the permitting stage, such as proximity requirements and location restrictions ($\tilde{c}_{\text{close}}$). However, it is only a partial shield: ongoing compliance costs such as stricter emission controls and more frequent inspections reduce the net present value of drilling regardless of when the permit was obtained ($\tilde{q}$). This captures what Kellogg [2024] terms the disinvestment effect.

Anticipation beliefs. During 2017, firms had no reason to expect regulatory change ($\gamma = 0$). The event study estimates in Figure 2 show no significant effects on permitting or drilling in 2018Q1 or 2018Q2, so we calibrate $\gamma = 0$ for these quarters as well.[19] We estimate $\gamma = \gamma_{\text{Q3}}$ for 2018Q3 and $\gamma = \gamma_{\text{Q4}}$ for 2018Q4, allowing beliefs to increase as the ballot initiative approached the November 2018 election.

[18] Recall that the regulator paused permit approvals for wells within 1,500 feet of homes and subsequently codified stricter requirements under the 2019 legislation [Finley, 2019].

[19] In principle, these could be estimated, but the event study estimates are indistinguishable from zero in these quarters; calibrating directly simplifies estimation without affecting results.

Calibrated parameters. Table 4(b) shows the calibrated parameters. We set the quarterly discount factor to $\beta = 0.95$ and calibrate the drilling cost to $c_{\text{drill}} = \$6.0$ million.[20] The permit cost $c = \$3{,}000$ reflects application paperwork burden and state filing fees.[21] The lifetime production value $q = \$6.60$ million is based on average first-36-month gross revenue of \$5.9 million for wells drilled during the pre-regulation period (2017), extrapolated to a lifetime present value via a standard decline curve (Appendix C.1). In Appendix C.2, we show that counterfactual results are robust to alternative assumptions on the calibrated parameters.

5.2 Identification

We target 18 empirical moments, many constructed from the event study estimates in Section 3. The identification arguments can be classed into three groups.

Pre-regulation steady state. The drilling dispersion parameter σ_{drill} governs how drilling is distributed across the permit life. The share of permits exercised in their first year pins down this parameter. Lower σ_{drill} concentrates drilling into early quarters; higher σ_{drill} spreads it more evenly. We also match the probability that a permit is ever drilled. We include a moment for the fraction of wells drilled near buildings in the pre-regulation period, which identifies the share of close prospects. In total we use three moments from the pre-regulation period (2017).

Post-regulation dynamics. Post-regulation drilling event study coefficients identify the realized regulatory cost $\tilde{q}$ (4 moments).[22] The difference-in-difference in proximity between

[20] The EIA reports an average drilling cost of \$717 per foot for crude oil wells in 2007, the most recent year available [U.S. Energy Information Administration, 2016]. Adjusting for CPI inflation to 2018 yields approximately \$869 per foot. At the average depth of Colorado wells in the Niobrara formation of the DJ Basin (approximately 7,000 feet; [American Association of Petroleum Geologists, 2024]), this implies a drilling cost of approximately \$6.0 million per well.

[21] Federal permit applications require approximately 8 hours of preparation [Bureau of Land Management, 2023]. At Colorado attorney rates of \$300/hour [Clio, 2024] plus filing fees of approximately \$200, this yields roughly \$3,000 per permit.

[22] The post-regulation drilling pattern also reflects the depletion of grandfathered permits acquired during anticipation: as the stock of active permits falls, drilling declines mechanically even without a payoff change. Because the model tracks these stock dynamics explicitly, $\tilde{q}$ is identified from the decline in drilling that remains after accounting for stock depletion.

grandfathered and non-grandfathered wells pins down the close-well surcharge $\tilde{c}_{\text{close}}$ (1 moment).

The permitting dispersion σ_{permit} is harder to pin down directly, since our data contain only successful permit applications, and not the underlying choice of whether to seek a permit. Instead, the *dynamics* of the post-regulation permit event study coefficients identify this parameter as permitting adjusts from its post-surge level toward a new steady state. Intuitively, if σ_{permit} is too low, the permit decision is nearly deterministic, producing sharp, lumpy dynamics. If σ_{permit} is too high, choices become insensitive to the regulatory change, producing flat, slow adjustment. The observed transition path pins down σ_{permit} (4 moments).

Anticipation parameters. With σ_{drill}, σ_{permit}, $\tilde{q}$, and $\tilde{c}_{\text{close}}$ identified from pre- and post-regulation moments, the remaining anticipation parameters — beliefs γ_{Q3} and γ_{Q4}, and anticipated regulatory cost $\hat{q}$ — are identified by the permit and drilling event study coefficients in 2018Q3 and 2018Q4 (4 moments).[23] To build intuition, suppose we initially set $\hat{q} = 0$. The permit surge moments then pin down γ_{Q3} and γ_{Q4}, since these beliefs drive the rush for grandfathered permits. However, with $\hat{q} = 0$ the drilling payoff is unchanged, so the additional active permits generate a drilling *increase*, the opposite of what we observe. Increasing $\hat{q}$ reduces the drilling payoff and matches the observed drilling decline. In this way, the permit surge identifies beliefs while the drilling response separately identifies the anticipated cost.

5.3 Estimation and Results

We estimate the remaining parameters by simulated method of moments (SMM), minimizing $\hat{\theta} = \arg\min_{\theta}[m(\theta)-\hat{m}]'[m(\theta)-\hat{m}]$, where θ is the parameter vector, $m(\theta)$ are model-predicted moments, and $\hat{m}$ are empirical moments. We use an identity weighting matrix, appropriate here because all moments are on comparable scales. Confidence intervals are computed via the bootstrap with 200 replications. The model matches the targeted moments closely (Table

[23]For completeness, we also include 2018Q1 and 2018Q2 drilling event study coefficients. However we do not include the respective moments for permitting because the parameters they identify (the γ in these periods) we calibrate to 0, as previously discussed.

Table 5: Estimated parameters

Parameter	Description	Estimate	95% CI
σ_{permit}	Choice dispersion (permit)	0.05	[0.04, 0.05]
σ_{drill}	Choice dispersion (drill)	0.04	[0.03, 0.06]
π_{close}	Share of close prospects	0.35	[0.27, 0.46]
γ_{Q3}	Anticipation belief (2018Q3)	0.08	[0.03, 0.11]
γ_{Q4}	Anticipation belief (2018Q4)	0.32	[0.24, 0.46]
$\hat{q}$	Anticipated regulatory cost ($M)	0.61	[0.52, 0.71]
$\tilde{q}$	Realized regulatory cost ($M)	0.05	[0.04, 0.06]
$\tilde{c}_{\text{close}}$	Additional cost for close wells ($M)	0.08	[0.05, 0.10]

Note: SMM estimates with bootstrap 95% confidence intervals (200 replications).

8, Appendix A.4). Table 5 reports the estimates.

Beliefs about regulation formed gradually. We estimate that firms assigned a $\gamma_{\text{Q3}} = 0.08$ probability to regulation in 2018Q3, rising to $\gamma_{\text{Q4}} = 0.32$ by 2018Q4 as the election approached. Since the anticipated regulation was effectively a ban on new permitting ($c_{i,r} = \infty$), even a low probability spurs a rush for permits, since a firm without a permit faces a chance of permanently losing the option to drill.

We find that drilling decisions are more precise ($\sigma_{\text{drill}} = 0.04$) than permitting decisions ($\sigma_{\text{permit}} = 0.05$), though the confidence intervals overlap. One interpretation is that the permitting process reveals site-specific cost information, so that by the drilling stage firms face less residual uncertainty.

Consistent with the institutional details, firms over-anticipated the regulation. This also extends to the anticipated ongoing compliance costs of drilled wells under the anticipated regulation. Concretely, the anticipated cost $\hat{q} = \$0.61$ million; the realized regulation imposes $\tilde{q} = \$0.05$ million for all wells.

This over-anticipation drives the permit surge documented in Section 3. Firms stockpile grandfathered permits against an expected ban. When the weaker version of the regulation is implemented, these permits are most valuable for close wells since they allow firms to bypass the additional permitting cost of $\tilde{c}_{\text{close}}$. The permits acquired during anticipation therefore partially undo the regulation's intended effect on drilling near buildings. We quantify this

leakage in the next section.

6 Counterfactuals

6.1 Overview

We use the estimated model to quantify the health cost of anticipation and grandfathering. Starting from the implemented regulation — where firms anticipate during 2018Q3–Q4 and pre-regulation permits are grandfathered — we simulate counterfactual policies that sequentially remove these features. Without grandfathering, all post-regulation drilling faces the regulatory cost regardless of permit timing. Under surprise regulation, firms receive no advance warning; regulation arrives unexpectedly in 2019Q1.

We report results in two panels. Panel A reflects our baseline estimates, where firms anticipate regulation but overestimate its stringency ($\hat{q} > \tilde{q}$). Panel B considers perfect foresight, where the harsh anticipated regulation materializes — including a complete ban on new permitting.

In both panels, we focus on health-weighted drilling, where wells are weighted by proximity to populated areas.[24] We report changes relative to the implemented regulation, so positive values indicate a reduction in health-weighted drilling. In Appendix C.2, we show that these results are robust to alternative assumptions on the calibrated parameters.

6.2 Results

Table 6 reports the counterfactual results, and Figure 4 shows the dynamics of permits and drilling under each scenario.

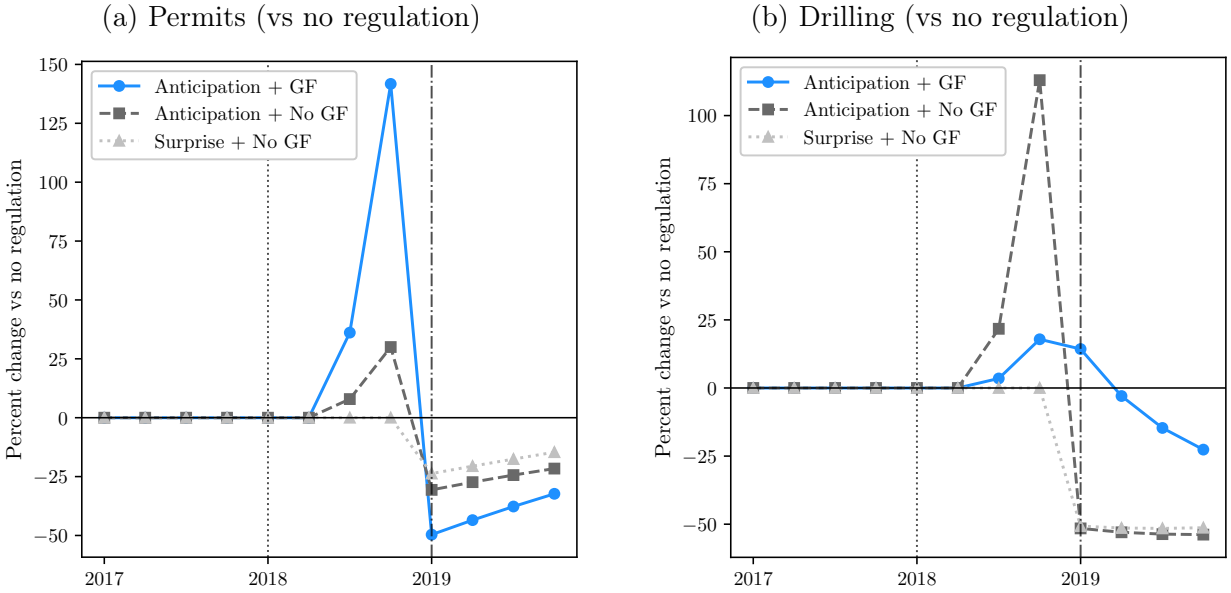
[24]Recall from Section 2.2 that we construct well-level health exposure measures using a concentric ring analysis. For each permitted well, we count residential buildings within 16 distance bands from 0–150 feet to 1,800–2,000 feet (Figure 7) and weight each building by the acute non-cancer hazard index at its distance (Figure 8; ICF [2019]). Averaging across close and far wells yields health weights of 1.26 and 0.11respectively. A reduction in health-weighted drilling therefore corresponds directly to fewer people exposed at health-relevant distances.

Table 6: Health effects of policy design

Policy Design	Health Effect	Anticipation Period		Post-Regulation
		Permits	Drilling	Drilling
Panel A: Baseline (implemented regulation ≠ expected regulation)				
Baseline (anticipation + grandfathering)	—	—	—	—
Change from baseline:				
Remove grandfathering	+27%	-23%	+25%	-50%
Also remove anticipation	+13%	-6%	-30%	+2%
= Total change	+40%	-30%	-5%	-48%
Panel B: Perfect foresight (implemented regulation = expected regulation)				
Baseline (anticipation + grandfathering)	—	—	—	—
Change from baseline:				
Remove grandfathering	+46%	-23%	+25%	-100%
Also remove anticipation	+13%	-6%	-30%	+0%
= Total change	+59%	-30%	-5%	-100%

Note: Changes are relative to the implemented regulation (anticipation + grandfathering). Health Effect is the percent reduction in health-weighted drilling; positive values indicate improvement. Other columns report percent changes in quantities. Rows are additive: each incremental change is expressed as a fraction of the baseline level.

Figure 4: Counterfactual permit and drilling dynamics



Note: Percent change relative to no regulation, which nets out the natural decline in drilling over this period. Vertical lines indicate referendum announcement (2018Q1) and regulation start (2019Q1).

Baseline results (Panel A). Removing grandfathering reduces health-weighted drilling by 27%. Without grandfathering, permits no longer lock in favorable treatment, so the permit stockpile cannot sustain drilling after regulation takes effect. Post-regulation drilling falls -50%. Firms that wish to avoid the new rules must instead drill sooner, and anticipation-period drilling *increases* +25% — the Green Paradox. Panel (b) of Figure 4 shows this substitution: the post-regulation permit overhang disappears and a pre-regulation drilling spike takes its place. This substitution illustrates the 'mirror image' structure of the permitting channel: under the implemented regulation, permits rush forward while investment does not; removing grandfathering flips this picture, so investment rushes forward while permits do not. Since drilling is expensive relative to permitting, the spike is far smaller than the overhang it replaces. Note that panel (b) shows the implemented policy still generates a small spike in anticipatory drilling relative to no regulation, so the Green Paradox is not completely eliminated. However, this spike is small enough to be masked in the descriptive evidence (Observation 2) by the field-level decline curve, which is netted out here. Removing grandfathering amplifies this effect substantially.

Additionally, removing anticipation through a 'surprise regulation' yields an additional 13 percentage point health gain. Without advance warning, firms cannot stockpile permits or accelerate drilling before regulation takes effect. Anticipation-period permits and drilling return to baseline levels. Panel (a) of Figure 4 shows the permit surge concentrated in the anticipation window; removing anticipation eliminates this channel. Overall, removing both features reduces health-weighted drilling by 40%, with grandfathering accounting for the majority of the total.

Perfect foresight (Panel B). Panel B considers a counterfactual where the harsh anticipated regulation materializes, including a complete ban on new permitting. Anticipation-period dynamics are identical to Panel A since firms respond to the same expected regulation, but the harsher realized regulation makes grandfathered permits more valuable.

Removing grandfathering now reduces health-weighted drilling by 46%, compared to 27% in Panel A. Under a permit ban, non-grandfathered permits cannot be replaced if they

expire, which eliminates the option value of waiting and drives post-regulation drilling to zero. Additionally removing anticipation adds 13 percentage points. The total health gain from removing both features is 59%.

Overall, both panels point to the same conclusion. Grandfathering is the dominant source of health cost, and harsher regulation amplifies the problem by increasing the value of grandfathered permits. Grandfathered permits are valuable because they shield firms from regulatory costs; stricter rules therefore make permits more valuable, attracting more stockpiling and generating more leakage. Eliminating grandfathering provisions would capture a substantial proportion of the achievable health gain, even when firms anticipate the regulation.

7 The permitting channel in other markets

The permitting channel operates whenever firms hold real options that can shield them from regulation, have advance notice, and existing permits are grandfathered. We document this pattern across oil and gas, housing, and electricity markets. In each case, permits surge in anticipation of regulation while investment remains stable.

Oil and gas markets California's 2024 setback regulation satisfies all three conditions. The regulation restricted new permits for drilling near occupied buildings and grandfathered existing approvals [CalGEM, 2024].[25] Subfigure 5a shows that firms responded by acquiring permits at more than ten times the baseline rate in the months before the regulation took effect. Drilling activity, shown by the gray dashed line, remained stable. Consistent with the permitting channel, firms locked in regulatory treatment through cheap permits without accelerating investment.

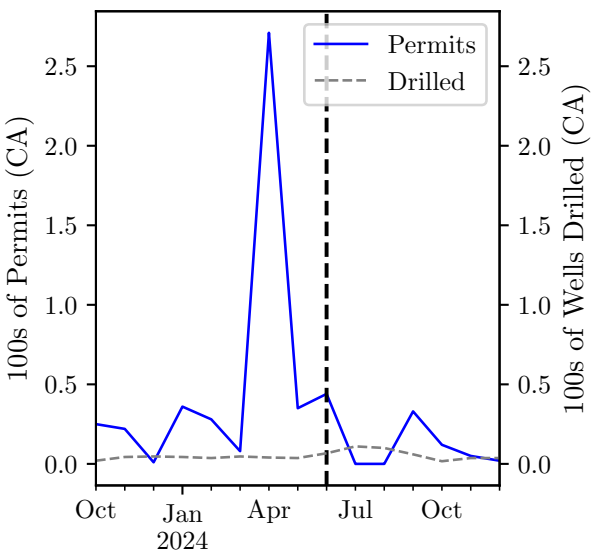
Subfigure 5b shows an analogous pattern in federal oil and gas permitting ahead of Joe Biden's announced freeze on new permits.[26] The proposed ban targeted new permits, firms had advance notice from the 2019 campaign announcement, and existing permits would

[25]Wells drilled under grandfathered permits were still subject to some additional requirements, such as neighbor notification [CalGEM, 2024].

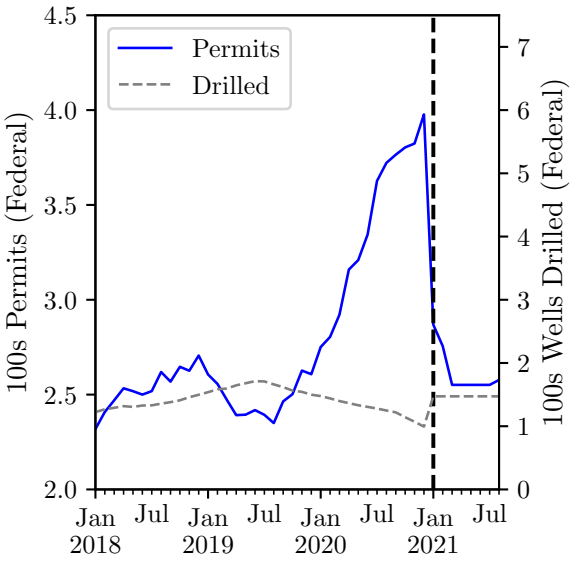
[26]The freeze was part of Biden's climate plan [Biden for President Campaign, 2019], announced in May 2019 [Axios, 2019]. The ban was never fully implemented [Brown, 2021].

Figure 5: Anticipatory responses on permits in other markets

(a) California setback regulations



(b) Biden's announced freeze on new permits



Note: Panel (a) — the dashed vertical line shows the introduction of the Californian regulation in June 2024. The blue line/left axis shows the number of approved permits (in 100s) in California. The gray dashed line/right axis shows the number of wells spudded in California. Panel (b) — the dashed vertical line shows the (expected) introduction of the Federal regulation in January 2021. The blue line/left axis shows the number of approved permits (in 100s) for Federal wells. The gray dashed line/right axis shows the number of federal wells spudded (12-month rolling average). In both panels, permits spike in anticipation of regulation while drilling activity remains stable. Figure 9 (Appendix) shows the same permit series with Texas permits as a control.

be exempt. Permits on federal land spiked in the lead-up to January 2021 while drilling remained stable.

Housing markets The permitting channel extends beyond energy markets. For example, New York City's '421-a' program provides a partial property tax exemption for new multifamily housing construction. When the program faced expiration in June 2015, building permits filed before the deadline locked in the existing tax treatment for the life of the project [NYU Furman Center, 2015]. Figure 10 (Appendix) shows that the city authorized nearly 34,000 residential units in Q2 2015, more than five times the typical quarterly level. In other words, developers acquired real options to build under favorable tax treatment.

Electricity markets Another example of the permitting/real options channel is in electricity markets in China. Here, construction approvals for new coal power plants function as options that lock in the right to build under the current policy. After the central government signaled in 2021 that it would soon restrict new coal capacity, local governments approved 152 GW of new capacity between early 2022 and mid-2023. This was a four-fold increase over the previous five years [Centre for Research on Energy and Clean Air, 2023]. Investment did not increase at the same rate: of the 218 GW permitted since early 2022, fewer than half had started construction by the end of 2023 [Centre for Research on Energy and Clean Air, 2024].[27]

Overall, the 'mirror image' pattern holds across these settings: permits surge in anticipation of regulation while physical investment remains stable.

8 Conclusion

We study how the permitting channel reduces the effectiveness of environmental regulation. When firms hold real options that can partially shield them from regulation, they can lock in favorable treatment by acquiring cheap permits without accelerating physical investment.

[27] A subsequent industry report noted the resulting permit overhang: "The commissioning boom of 2025 reflects a delayed response to the permitting surge of 2022–2023, when more than 100 GW of coal power was approved each year. Unless policy action is taken, these previously approved projects will continue to drive high levels of commissioning in 2026–2027" [Centre for Research on Energy and Clean Air, 2025].

Using Colorado's 2019 oil and gas reforms, we document a 'mirror image' of the standard Green Paradox prediction: permits surge before regulation takes effect, but drilling does not. Grandfathered permits then allow firms to drill near homes after regulation, bypassing the setback provisions the regulation was designed to enforce. Our structural estimates confirm that removing the permitting channel *improves* health outcomes despite amplifying anticipatory investment: without cheap permits, firms must accelerate costly drilling, and fewer do. Health-weighted drilling near homes falls by 27%, and removing both grandfathering and anticipation achieves a 40% total reduction.

The permitting channel potentially operates wherever firms can access real options that can shield them from regulation and have advance notice of the change. We document analogous patterns in California's setback regulations, federal oil and gas permitting, New York City housing, and Chinese coal plant approvals. In each case, permits spike before regulation while physical investment remains stable. This pattern is invisible to the standard test for anticipatory effects, which measures whether investment accelerates before regulation. When permits separate regulatory lock-in from the investment itself, a finding of no preemptive investment can coexist with substantial regulatory leakage. Overall, our results show that the permitting channel can be a first-order source of regulatory leakage.

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A Model Appendix

We provide additional details on the model. Section A.1 describes the computation of steady states and value functions, Section A.2 provides full payoff expressions, and Section A.3 describes the simulation algorithm.

A.1 Computation of Steady States

The model requires computing three steady-state value functions, one for each regulatory regime: pre-regulation, anticipated, and realized.

Regime definitions Let $r \in \{\text{pre-regulation}, \text{anticipated}, \text{realized}\}$ denote the regime. Each regime implies different drilling payoffs $\pi_{i,r}$. For computational purposes, we distinguish the anticipated post-regulation regime (computed using $\hat{q}$) from the realized post-regulation regime (computed using $\tilde{q}$).

Fixed-point iteration For a given regime r, we must solve for the steady-state value functions $\bar{P}_{i,r,\tau}$ and $\bar{W}_{i,r}$. These are coupled: the value of a permit at $\tau = 0$ depends on the unpermitted value $\bar{W}_{i,r}$, while the unpermitted value depends on the value of obtaining a new permit at $\tau_{\max}$. We solve for them using nested fixed-point iteration:

1. *Initialize*: Set $\bar{W}_{i,r}^{(0)} = 0$ for all i, where the superscript (n) denotes the iteration count.
2. *Inner loop (permitted values)*: Given $\bar{W}_{i,r}^{(n)}$, solve backwards from $\tau = 0$ to $\tau = \tau_{\max}$. At $\tau = 0$:

$$\bar{P}_{i,r,0}^{(n)} = \sigma_{\text{drill}} \cdot \log\left(\exp\left(\frac{\pi_{i,r}}{\sigma_{\text{drill}}}\right) + \exp\left(\frac{\beta \bar{W}_{i,r}^{(n)}}{\sigma_{\text{drill}}}\right)\right) + \sigma_{\text{drill}}\gamma^{\text{euler}} \tag{7}$$

For $\tau > 0$:

$$\bar{P}_{i,r,\tau}^{(n)} = \sigma_{\text{drill}} \cdot \log\left(\exp\left(\frac{\pi_{i,r}}{\sigma_{\text{drill}}}\right) + \exp\left(\frac{\beta \bar{P}_{i,r,\tau-1}^{(n)}}{\sigma_{\text{drill}}}\right)\right) + \sigma_{\text{drill}}\gamma^{\text{euler}} \tag{8}$$

Here, γ^{euler} is Euler's constant and the log-sum-exp formula gives the expected value

under logit shocks.

3. *Outer loop (unpermitted values)*: Update unpermitted values:

$$\bar{W}_{i,r}^{(n+1)} = \sigma_{\text{permit}} \cdot \log\left(\exp\left(\frac{-c_{i,r} + \bar{P}_{i,r,\tau_{\max}}^{(n)}}{\sigma_{\text{permit}}}\right) + \exp\left(\frac{\beta \bar{W}_{i,r}^{(n)}}{\sigma_{\text{permit}}}\right)\right) + \sigma_{\text{permit}}\gamma^{\text{euler}} \quad (9)$$

4. *Convergence*: Repeat steps 2–3 until $\|\bar{W}_{i,r}^{(n+1)} - \bar{W}_{i,r}^{(n)}\|_\infty < \epsilon$ for sufficiently small tolerance ϵ.

Anticipation regime In the anticipation regime, we impose that no new permits can be obtained if regulation occurs. This reflects firms' expectation that permitting will be banned under the anticipated regulation. Formally, $\bar{W}_{i,\text{ant}} = 0$, and only the permitted value function $\bar{P}_{i,\text{ant},\tau}$ is computed. Intuitively, if firms expect a permit ban, an unpermitted prospect has zero option value since firms cannot obtain permits to drill later. We solve the anticipation regime via backwards induction, starting from T-1 (one period before regulation) and proceeding backwards to T-2, etc.

A.2 Full Payoff Expressions

Drilling payoffs by regime Table 7 reports the complete drilling payoffs for all regime-state combinations.

Table 7: Drilling payoffs by regime, type, and grandfathering status

	Pre-regulation	Anticipated	Realized
Far, $g = 1$	$q - c_{\text{drill}}$	$q - \hat{q} - c_{\text{drill}}$	$q - \tilde{q} - c_{\text{drill}}$
Far, $g = 0$	—	—	$q - \tilde{q} - c_{\text{drill}}$
Close, $g = 1$	$q - c_{\text{drill}}$	$q - \hat{q} - c_{\text{drill}}$	$q - \tilde{q} - c_{\text{drill}}$
Close, $g = 0$	—	—	$q - \tilde{q} - c_{\text{drill}} - \tilde{c}_{\text{close}}$

Note: Entries marked "—" are not applicable because $g = 0$ only occurs post-regulation ($t \geq 9$). All wells face $\tilde{q}$ post-regulation; grandfathering ($g = 1$) only exempts from $\tilde{c}_{\text{close}}$.

Recall the notation from the main text: $\hat{q}$ is the anticipated regulatory cost, $\tilde{q}$ is the realized cost, and $\tilde{c}_{\text{close}}$ is the close-well increase in permitting cost under the realized regulation.

A.3 Simulation Algorithm

We simulate drilling and permitting behavior forward in time, taking the computed steady states and choice probabilities as inputs.

State variables The simulation tracks two objects:

- $N_t^U(d)$: Mass of unpermitted prospects of type d at start of period t
- $N_t^P(d, \tau, g)$: Mass of permitted prospects by type, maturity, and grandfathering status

Initialization At $t = 1$, we initialize permit stocks to the pre-regulation steady state, reflecting the approximate industry steady state before anticipation began:

$$N_1^P(d, \tau, g = 1) = \bar{N}_{\text{steady}}^P(d, \tau) \qquad \text{for } \tau \in \{0, 1, \ldots, 7\} \tag{10}$$

where $\bar{N}_{\text{steady}}^P$ is computed from the steady-state distribution under the pre-regulation regime. Under pre-regulation, firms permit and drill at constant rates; over time, the distribution of permits across maturity levels stabilizes as new permits entering at $\tau = 7$ balance permits leaving through drilling or expiration. We initialize at this steady-state distribution so that all dynamics in the simulation arise from anticipation and regulation, not from arbitrary starting conditions.

Period-by-period transitions Within each period t, the simulation proceeds as follows:

1. *Compute value functions*: Calculate $P_{i,t,\tau}$ and $W_{i,t}$, given the current regime at t.
2. *Drilling from permits*: For each (d, τ, g), the mass that drills is:

$$\text{Drills}_t(d, \tau, g) = N_t^P(d, \tau, g) \cdot \Pr(\text{drill} \mid d, \tau, g, t) \tag{11}$$

3. *Permit applications*: Unpermitted prospects that obtain permits:

$$\text{NewPermits}_t(d) = N_t^U(d) \cdot \Pr(\text{permit} \mid d, g, t) \tag{12}$$

New permits receive $g = 1$ if issued before T and $g = 0$ otherwise.

4. *Update permit stocks*: Permits age by one quarter. For $\tau \in \{0, \ldots, 6\}$:

$$N^P_{t+1}(d, \tau, g) = N^P_t(d, \tau + 1, g) \cdot \Pr(\text{wait} \mid d, \tau + 1, g, t) \tag{13}$$

New permits enter at $\tau = 7$:

$$N^P_{t+1}(d, 7, g) = \text{NewPermits}_t(d) \tag{14}$$

Aggregation Total drilling in period t is:

$$\text{TotalDrills}_t = \sum_d \left(\text{ImmediateDrills}_t(d) + \sum_{\tau, g} \text{Drills}_t(d, \tau, g) \right) \tag{15}$$

A.4 Model Fit

Table 8: Model fit: Empirical vs. simulated moments

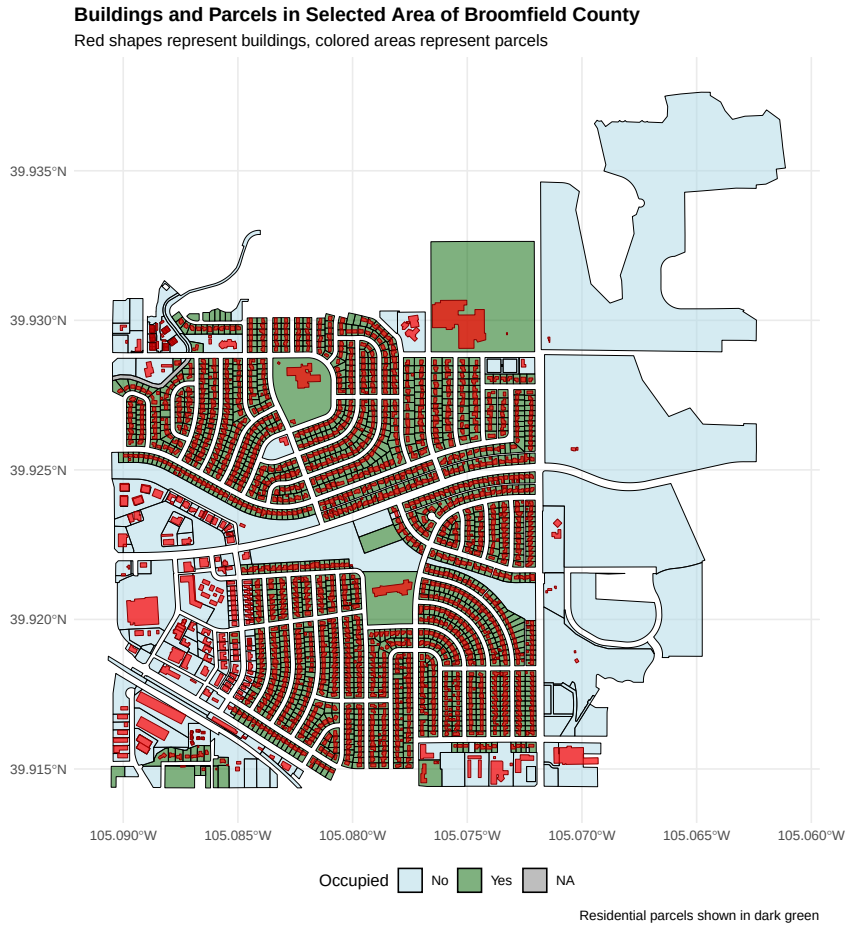
Moment	Empirical	Simulated
Permit applications		
Permits % change (2018Q3)	0.250	0.227
Permits % change (2018Q4)	1.09	1.07
Permits % change (2019Q1)	-0.212	-0.529
Permits % change (2019Q2)	-0.677	-0.512
Permits % change (2019Q3)	-0.456	-0.498
Permits % change (2019Q4)	-0.751	-0.486
Drilling rates		
Drilling % change (2018Q1)	-0.090	-0.060
Drilling % change (2018Q2)	-0.123	-0.108
Drilling % change (2018Q3)	-0.120	-0.121
Drilling % change (2018Q4)	-0.062	-0.046
Drilling % change (2019Q1)	-0.207	-0.096
Drilling % change (2019Q2)	-0.282	-0.249
Drilling % change (2019Q3)	-0.294	-0.363
Drilling % change (2019Q4)	-0.340	-0.447
Grandfathering effects		
Close share diff. (g=0 vs g=1)	-0.348	-0.289
Pre-regulation behavior		
Prob. drill in first year	0.817	0.794
Share close to buildings	0.400	0.355
Pr(drill | permit) (2017)	0.564	0.530

B Data Construction

Building classification The Microsoft US Building Footprints Project provides building outlines but no information on property characteristics. We supplement this with parcel-level data from Regrid, which provides Land-Based Classification Standards (LBCS) functional codes categorizing property use. We classify buildings as residential if they fall within parcels coded as: single-family residential (1000), multi-family residential (1100), mobile home parks (1200), group quarters (1300), or residential hotels (1330). We match buildings to parcels by determining which parcel contains each building's centroid. Figure 6 illustrates the classification for a sample area. We calculate distances between wells and nearby buildings using the NAD83 / UTM Zone 13N coordinate system.

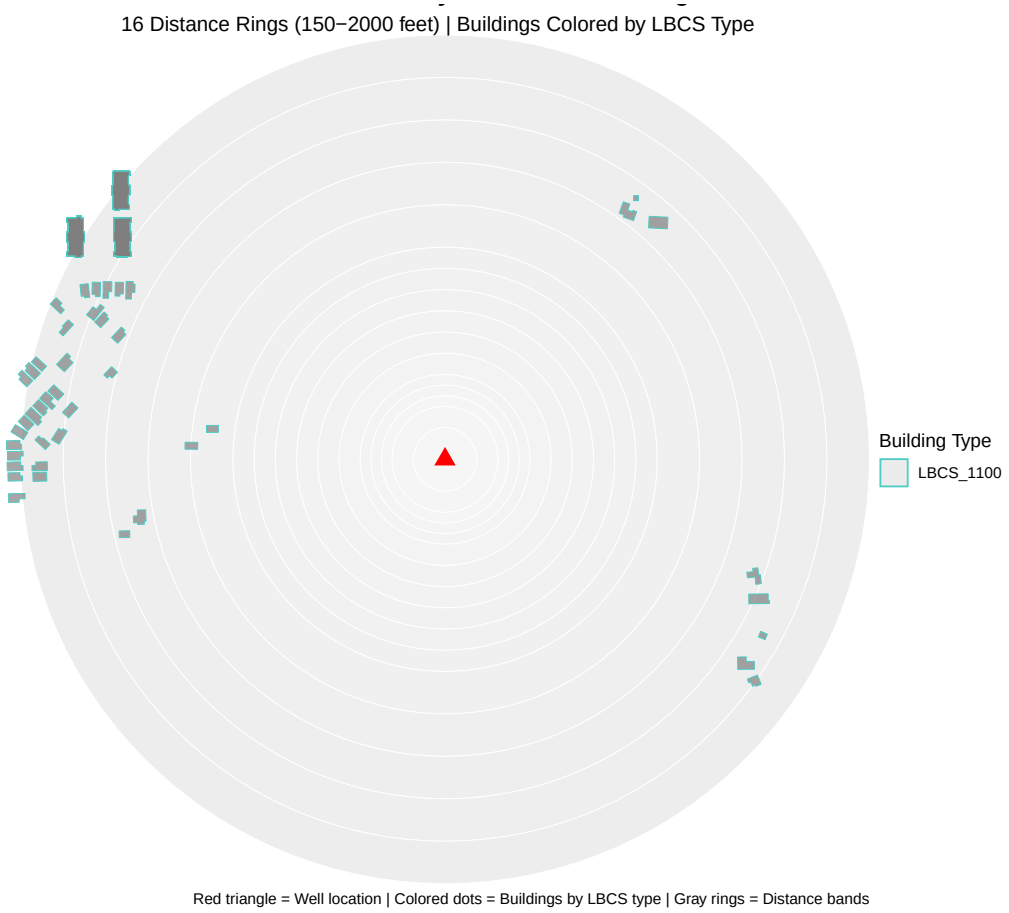
Concentric ring analysis We conduct a 'donut' analysis that counts buildings within concentric distance rings around each well location. We define 16 distance bands ranging from 0–150 feet (Ring 1) to 1,800–2,000 feet (Ring 16), with finer resolution at closer distances where health impacts are largest. We first pre-filter the building dataset by creating a buffer around all wells at 2,000 feet, reducing the dataset by 20–60%. We then compute a single distance matrix between wells and remaining buildings using vectorized spatial algorithms in the NAD83 / UTM Zone 13N coordinate system, and use logical operations on this matrix to count buildings within each ring simultaneously. Figure 7 shows an example for a single well, and Figure 8 plots the health hazard indices by distance.

Figure 6: Occupied parcels in Broomfield



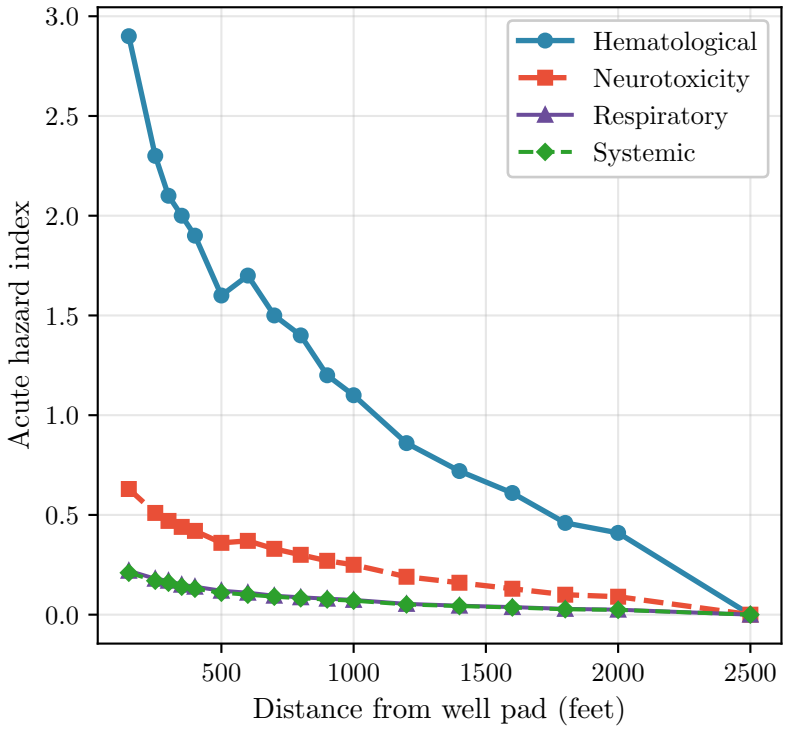
Note: Example of building classification in Broomfield County, Colorado. Residential parcels (classified using LBCS codes) are shown in color. Building footprints from Microsoft US Building Footprints are matched to parcel data from Regrid to determine occupancy status.

Figure 7: Distribution of buildings around well 24126



Note: Example of concentric ring analysis for a single well. Each bar shows the count of buildings within the specified distance band from the well location. Distance bands range from 0–150 feet to 1,800–2,000 feet.

Figure 8: Acute health hazard indices by distance from well pad



Note: Acute non-cancer hazard indices from ICF [2019], Table E-31, for oil and gas production activities at a Northern Front Range site. Each line shows the hazard index for a different critical-effect group. The study models receptors at 16 distance rings from 150 to 2,000 feet (Table 2-9); we set the hazard index to zero at 2,500 feet because the study does not model beyond 2,000 feet and hazard indices are already near zero at that boundary.

C Calibration and Robustness

C.1 Calibration of Lifetime Production Value

Gross revenue from production data. We compute gross hydrocarbon revenue for each well using Enverus data on first-36-month oil and gas production. Oil production (in barrels) and gas production (in MCF) are converted to a common unit—barrels of oil equivalent (BOE)—using the standard thermal equivalence of 5.8 MCF per BOE. We then value total BOE at \$65 per barrel, approximately the average WTI crude oil price over the 2017–2019 sample period [U.S. Energy Information Administration, 2026]. Averaging across horizontal wells spud in Colorado in 2017 yields gross first-36-month revenue of \$5.9 million per well. Wells in our sample are predominantly oil producers, with gas contributing a small share of total BOE.

Lifetime present value via decline curve. Since wells continue producing beyond 36 months at declining rates, we convert the observed first-36-month revenue to a lifetime present value using a hyperbolic decline curve.

Concretely, hydraulically fractured horizontal wells exhibit high initial production rates followed by steep decline. We model this using the Arps hyperbolic curve with exponent $b = 1$ (harmonic decline), consistent with Wachtmeister et al. [2017] and Younk [2021].[28] Total well life is set to 30 years, consistent with the EIA's decline curve methodology [U.S. Energy Information Administration, 2024].

With a quarterly discount factor of $\beta = 0.95$, approximately 72% of the discounted lifetime production value accrues in the first 36 months. Applying the decline curve to the observed \$5.9 million in first-36-month revenue yields a lifetime present value of $q = \$6.6$ million.

[28] We set the initial decline rate to $D_i = 0.7$ per year, reflecting the steep early-life decline typical of Colorado Niobrara wells. The decline transitions from hyperbolic to exponential when the instantaneous decline rate falls to 10% per year, which occurs approximately 19 years into the well's life.

C.2 Calibration Robustness

Table 9 reports the policy erosion decomposition under alternative variations in parameters. The results are robust across all specifications.

Table 9: Sensitivity of counterfactual results to calibrated parameters

	Health Effect (%)		
Variant	Remove GF	+ Remove antic.	= Total
Benchmark	27%	13%	40%
Permit cost (c)			
+10%	27%	13%	40%
−10%	27%	13%	40%
+20%	27%	13%	40%
−20%	28%	13%	40%
Net drilling profit ($\pi = q - c_{drill}$)			
+10%	20%	14%	34%
−10%	22%	14%	36%
+20%	33%	13%	46%
−20%	49%	8%	58%

Note: Benchmark column shows the ideal policy effect (surprise regulation without grandfathering) as percent change in health-weighted drilling relative to no regulation. Subsequent columns show how anticipation and grandfathering erode this effect, matching the decomposition in Table 6.

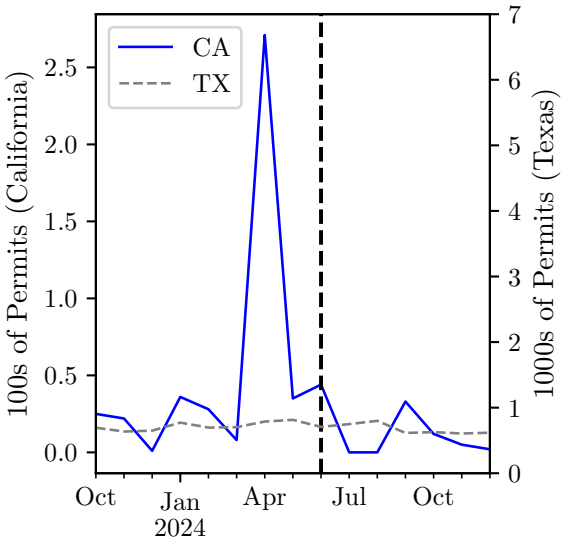
D Additional Figures

D.1 Other Markets: Permits Control Comparison

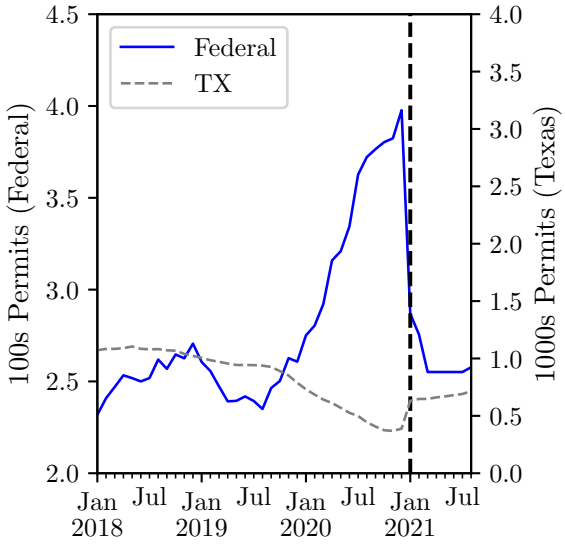
Figure 9 reproduces the permit series from Figure 5, replacing the drilling overlay with Texas permit approvals as a control group. Texas experienced no major regulatory changes during either episode, so stable Texas permitting rules out aggregate shocks as an explanation for the observed spikes.

Figure 9: Permits in other markets with Texas permits as control

(a) California vs. Texas permits

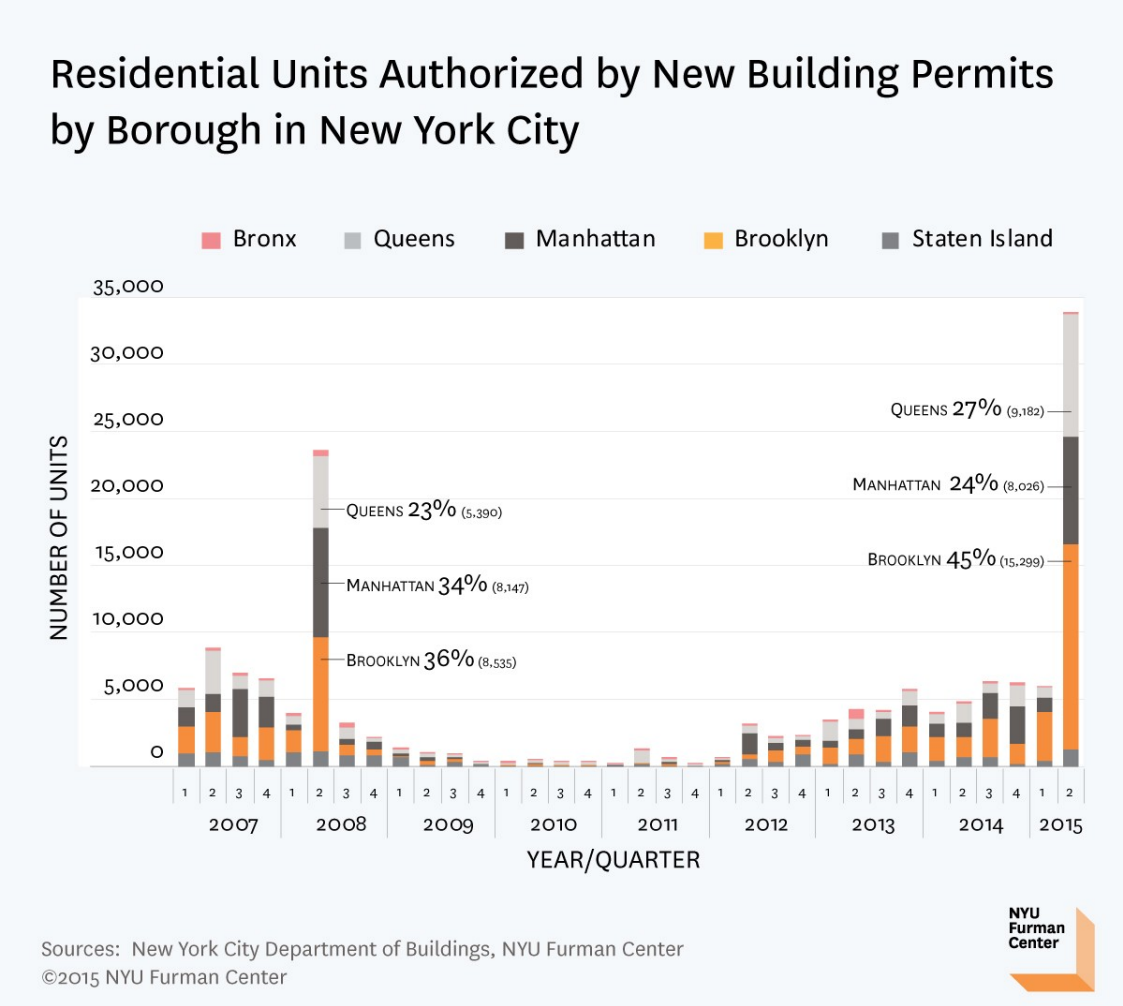


(b) Federal vs. Texas permits



Note: Panel (a) — the blue line/left axis shows approved permits (in 100s) in California; the gray dashed line/right axis shows approved permits (in 1000s) in Texas. Panel (b) — the blue line/left axis shows approved permits (in 100s) for Federal wells; the gray dashed line/right axis shows approved permits (in 1000s) in Texas. Texas experienced no major regulatory changes during either period.

Figure 10: New York City residential permit authorizations



Note: Quarterly residential units authorized in New York City. The spike in Q2 2015 corresponds to developers rushing to file permits before the 421-a tax exemption expired in June 2015. Source: NYC Department of Buildings, NYU Furman Center.