Permits as Real Options: Anticipation and Regulatory Leakage

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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 acquire the option to invest under current rules. Unlike the conventional Green Paradox response, this channel operates without accelerating physical investment and pollution. We develop a framework in which firms can use real options to avoid anticipated regulation. We estimate the framework using Colorado's oil and gas reforms, where permits surged before regulation but drilling did not. Policy-relevant designs that remove the permitting channel substantially reduce the health risks from 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 or physical activity in anticipation of future regulation. Green Paradox models emphasize this supply-side response.[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, from zoning to emissions permitting, 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 to the predictions of a standard investment-only model. Here, rather than moving forward investment, firms can temporarily avoid the regulation by acquiring a relatively low-cost permit. In contrast to the conventional Green Paradox response of intertemporal leakage, permits surge before regulation takes effect, but the investment (and consequent pollution) they authorize occurs *afterwards*. Moreover, because options are cheap relative to the investment they authorize, this channel can amplify anticipatory effects of regulation.

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 evidence that anticipated regulation spurred firms to acquire permits, but not increase drilling, before the regulation was implemented. As well, grandfathered permits are used for wells closer to residences,

[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 physical 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 i.e., proximity to drilling is a first-order determinant of health risk.

which tend to have higher health risk. Next, based on this evidence, we estimate a dynamic discrete choice model of permit acquisition and drilling.[3] Finally, we evaluate counterfactual policy designs and show that removing the permitting channel reduces health risk by 28%, with small effects on production, even though it induces firms to accelerate drilling before regulation takes effect.

Although our focus is on oil and gas in Colorado, the economic channel is much broader. It could potentially operate in any setting where two conditions hold: firms can access real options that can shield them from regulation, and they 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 since these two conditions are present. Drilling permits awarded before the regulation exempted firms from the new rules and firms received advance notice of the changes. Specifically, a 2018 ballot initiative proposed setbacks from occupied buildings (and "vulnerable areas" such as waterways and reservoirs), which would have effectively halted new drilling across most of the state.[4] The referendum failed, but a newly elected governor implemented a weaker version of the rules in early 2019.

We begin by documenting three observations. The first two use synthetic diff-in-diff event studies. First, we show that permit approvals spiked to 63.0% above their synthetic counterfactual in anticipation of the regulation. Second, drilling was 11.4% below the synthetic counterfactual during the same period. Third, wells drilled under permits approved post-regulation are 34.2% less likely to be drilled close to buildings; as a result, they have substantially lower health risk.

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

[4] Although the industry and the regulator's analysis concluded the regulation would effectively ban most new drilling, there was some debate around this question, and we discuss this further in Sections 2 and 3.

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 the anticipated regulation as preventing new permit issuance and therefore future drilling of unpermitted prospects, while also increasing ongoing compliance costs for all wells. The model also accommodates that the regulation ultimately implemented was weaker than the anticipated regulation.

If a firm obtains a permit before the regulation then that prospect is grandfathered from the new setback rules i.e., the firm can continue to drill close to occupied buildings. However, these grandfathered permits may not shield firms from other increases in ongoing compliance costs from the regulation that affect all wells regardless of when they are drilled. Given this institutional structure, firms can respond to the anticipated regulation in several ways: they can accelerate drilling, acquire a permit and wait, or do nothing and face the new regime. Overall, the model embeds three key effects. The first two are documented in the previous literature — a potential anticipatory investment response emphasized by Green Paradox models, 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. To do so, we leverage our descriptive evidence, which includes targeting the event-study estimates for permitting and drilling. For example, the permit surge during the anticipation period assists in identifying firms' beliefs about the probability of regulation.

We use the estimated model to evaluate counterfactual policy designs compared to the empirical baseline.[5] First, we eliminate grandfathering so that all drilling faces new requirements regardless of when the permit was approved. This is not simply a theoretical exercise; pre-

[5]One may ask why regulators use grandfathering at all, given it inherently allows some firms to avoid the new regulation. One common justification is political reasons. For example, exempting incumbents from new requirements is often politically necessary to pass stricter standards [Nash and Revesz, 2007].

venting permit grandfathering is regularly employed in real-world policy design when rules change.[6] Firms can no longer avoid regulation through cheap permits and must instead accelerate costly drilling. Therefore, although this induces the anticipatory drilling response emphasized by Green Paradox models, it reduces health risk because fewer close wells are drilled. Concretely, health risk falls by 28%. Oil and gas production changes modestly.

Second, we remove anticipation, simulating a surprise regulation, which eliminates the anticipatory investment spike. This yields an additional 8 percentage-point health-risk improvement, for a total cumulative health-risk improvement of 36%, while reducing oil and gas production by 13%.

Overall, the permitting channel substantially undermines the regulation. Our findings also carry a methodological lesson. When firms hold real options that are grandfathered from new rules, the standard Green Paradox test — a spike in investment or pollution before the regulation — cannot rule out that firms avoided the anticipated rules. For example, the permitting channel shows up in our setting instead as a smaller decline in drilling after the regulation takes effect, concentrated near the homes the rules were meant to protect.

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 or pollution accelerates before regulation takes effect, motivated by the predictions of the Green Paradox theory. Examples include fossil fuel markets [Di Maria et al., 2014, Lemoine, 2017], freight truck purchases [Rittenhouse and Zaragoza-Watkins, 2018], fishing [McDermott et al., 2019], and consumer firearm purchases [Bollman et al., 2026]. Similarly, Costello and Grainger [2022] formalize the case where allowable future rights (to, for example, pollute) are determined by current usage levels, which gives agents an incentive to increase the regulated activity in the current period. By contrast, the permitting channel operates without accelerating the regulated activity and its realized effects

[6] For example, federal Title V air permits may be reopened when new applicable requirements arise and can be modified or revoked to ensure compliance [U.S. Environmental Protection Agency, 2026, 40 C.F.R. § 70.7(f)].

occur entirely after the regulation is implemented. Moreover, because acquiring an option may be far less costly than exercising it, this mechanism can substantially amplify anticipatory leakage.

Our second contribution is to provide evidence for the permitting channel, and to estimate a structural model that embeds it. We build on the literature on understanding oil and gas markets [Herrnstadt et al., 2024, Muehlenbachs et al., 2015, Lange and Redlinger, 2019, Boomhower, 2019, Kellogg, 2024]. We also build on dynamic models of firm behavior under uncertainty [Gowrisankaran et al., 2025, Kellogg, 2014]. We complement these literatures by incorporating the permitting channel into a dynamic model, allowing firms to separately time permit acquisition and investment.

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, 2023, Sileo, 2026, Johnston et al., 2023, Leisten and Vreugdenhil, 2026]. Grandfathered permits allow drilling in the locations the regulation was specifically designed to protect, generating health costs that alternative designs 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. During our study period, permits remained valid for two years [Colorado Oil and Gas Conservation Commission, 2019b, Rule 303.g.(1)]; if drilling did not commence within this window, the permit expired. The key institutional feature for our analysis is that permits partially lock in the regulatory regime at approval. The permitting restrictions we study apply to newly issued permits, while wells drilled under previously approved permits are grandfathered. The cost of a permit is low, consisting primarily of application fees and engineering documentation.[7]

One may ask whether firms can preserve the grandfathered status of a permit by extending it, or through other means such as commencing minimal wellsite preparation. However, neither strategy is feasible. First, the regulation provides that a drilling permit cannot be extended [Colorado Oil and Gas Conservation Commission, 2019b, Rule 303.g.(1)]. Instead, the permit must be refiled, which forfeits the grandfathered status. For the second strategy, preserving the regulatory status requires spudding (starting to drill) the well. This entails mobilizing a drilling rig and beginning drilling operations, which immediately incurs a substantial share of the total drilling cost. As well, once started, drilling cannot be paused without significant additional costs.[8] Also, the drilling data provide a direct check: if firms had somehow preserved permits by spudding and then suspending wells, we would still observe an increase in spudded wells, but we find no such increase (Section 3).

Our analysis covers three periods and Figure 1 summarizes the timeline. The *pre-anticipation period* spans 2012–2017 and serves as the pre-period for the synthetic diff-in-diff estimation (Section 3). The *anticipation period* (2018) began when firms learned of potential regulatory tightening through a referendum which would take place in Q4 2018.[9] The proposed initiative would have effectively halted new drilling across most of the state. Specifically, it proposed 2,500-foot setbacks from occupied buildings (and "vulnerable areas" such as 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].[10] In our data, 96% of wells drilled in 2017 were on non-federal land. We date the anticipation period from Q1 2018, when the

[7] We further discuss the cost of a permit later in the model estimation.

[8] For example, a suspended-operations well must have surface casing set and cemented, while temporary abandonment requires a mechanical-integrity test, continued bonding, and Director approval for extensions beyond six months [Colorado Oil and Gas Conservation Commission, 2019b, definition of "Suspended Operations Well" and Rule 319.b].

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

[10] Although the regulator and the industry both expected the setbacks to eliminate most drilling within the state, a key question is whether firms could simply drill further horizontally to access the same oil and gas deposits but with the surface location beyond the setback e.g., Ericson et al. [2020]. We test for this behavior in our data in Section 3 and find that such movements do not occur. As well, even if the proposed regulation would have had less substantial effects if implemented, for the purposes of our model, the critical input is that firms anticipated that it would and made choices accordingly.

ballot initiative was initially filed [Colorado Secretary of State, 2018].

The ballot initiative would have applied its setback requirements only to wells permitted on or after its effective date [Colorado Secretary of State, 2018, subsection (6)]. However, firms may also have viewed passage as a signal of stronger public support for subsequent regulation, including emissions controls or inspections affecting existing wells. Under this interpretation, obtaining a grandfathered permit would preserve access to a drilling location without insulating the firm from all future regulatory costs. We return to this distinction in Section 5.1, where we allow regulation to affect both permitting costs and drilling payoffs.

The *regulation period* spans 2019. Although the referendum failed, voters elected a new Democratic governor and legislative majority. 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 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.[11] We end the sample in Q4 2019 because Covid makes clean identification difficult in 2020.

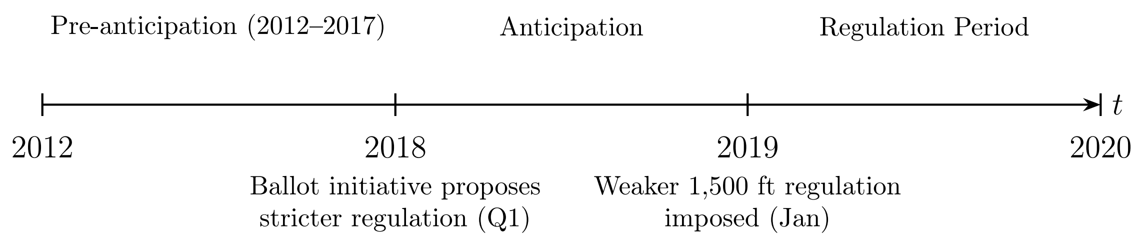
In all our results throughout the paper, we report health risk and oil and gas production separately rather than aggregating them into a single welfare number. We avoid a single welfare measure because it would require taking a stand on the social planner's weight on health risk relative to oil and gas production. These welfare weights are politically contested in our setting. Advocates framed the reform around health, while industry groups instead emphasized oil and gas production and the state economy [Legislative Council Staff, 2018].

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.

[11] Similar administrative criteria were set out in follow-up rules, such as the Director's Draft Objective Criteria in April 2019 [Colorado Oil and Gas Conservation Commission, 2019a]. A law was also passed in April 2019 (Senate Bill 19-181) that formalized additional regulations on the industry, but the provisions took effect in January 2021. We focus on the interim stringency imposed by the regulator in 2019.

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



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

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

		Summary Statistics				**Sample Composition**	
Variable	**Units**	**N**	**Mean**	**P10**	**P90**	**Category**	**Count**
Panel A: Production (First 3 Years, Drilled Wells)						*Geographic Distribution*	
$\log(1 + q_{oil})$ - Colorado	bbl	12,359	9.5	5.8	12.0	Total Permits	162,924 (100%)
$\log(1 + q_{oil})$ - Donor basins	bbl	109,447	9.2	0.0	12.6	Colorado	20,597 (12.6%)
$\log(1 + q_{gas})$ - Colorado	mcf	12,359	11.9	10.5	13.9	Donor basins	142,327 (87.4%)
$\log(1 + q_{gas})$ - Donor basins	mcf	109,447	11.6	0.0	14.9		
$\log(1 + \text{lateral})$ - Colorado	ft	8,600	8.7	8.3	9.2		
$\log(1 + \text{lateral})$ - Donor basins	ft	101,266	8.8	8.3	9.2		
Panel B: Spatial & Health (Colorado Permits)						Wells Drilled	121,806 (100%)
Distance to Building - Colorado	mi	20,597	2.2	0.2	6.0	Colorado	12,359 (10.1%)
Hematological Index - Colorado	index	20,597	0.4	0.0	1.4	Donor basins	109,447 (89.9%)
Neurotoxicity Index - Colorado	index	20,597	0.1	0.0	0.3		

Notes: P10 and P90 denote the 10th and 90th percentiles. Lateral length (the horizontal extent of the well) is measured in feet, and is not recorded for all wells. Health indices are acute non-cancer hazard indices from ICF [2019]. Donor basins pool the 16 non-Colorado basin aggregates used in the synthetic diff-in-diff analysis, selected as described in Section 2.2.

Permits and Wells. We obtain data from Enverus covering the complete universe of drilling permits and subsequent well development in Colorado. We also obtain Enverus data for comparison oil and gas basins in other states, which enter our synthetic difference-in-differences analysis as potential donors. We include non-Colorado basins in the top 15 oil and gas producing states. We subset to those basins with enough activity to form quarterly panels: permit donor basins must average at least 10 permit approvals per quarter during 2012Q1–2019Q4, while drilling donor basins must average at least 10 spudded wells per quarter over the same period.[12] We also exclude basins in the 'Western US Other' location, which has many missing well-type values, preventing us from consistently restricting donor wells to horizontal and directional wells.

Our data distinguish permits (approved applications) from wells (exercised permits). Our permit outcome therefore records approvals rather than application submissions. However, approval delays are typically short: in our sample, the median elapsed time from initial application submission to approval is 9 days. Table 1 reports 20,597 Colorado permits from Q1 2012 to Q4 2019, of which 12,359 resulted in drilled wells. Note that not all permits lead to drilling and some permits expire unused. Production data are available only for drilled wells. We exclude a small number of permits and wells (4% and 3%, respectively) in five counties—Boulder, Adams, 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 95% of Colorado permits during the sample period, 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.[13] We identify residential buildings using Land-Based Classification Standards (LBCS) codes. Appendix B provides details on the matching procedure;

[12] The exact cutoff is not consequential, and Appendix Table A.3 shows that the synthetic diff-in-diff estimates are robust to alternative donor pools and we discuss these tests further in Section 3.

[13] We also do a similar construction for Texas as a placebo check for Observation 3 of our descriptive evidence, reported in the Appendix.

Appendix Figure A.1 illustrates the classification for a sample area.

Health risk by distance. We obtain health risk using hazard indices from the Human Health Risk Assessment commissioned by the Colorado Department of Public Health and Environment [ICF, 2019]. This study evaluates the effects of different setback regulations on health risk in Colorado. We extract hazard indices by distance for four critical-effect groups from Table E-31 of the report: hematological, neurotoxicity, respiratory, and systemic. Each index is the ratio of modeled exposure to a reference level below which adverse effects are not expected. Appendix Figure A.3 plots the indices by distance. The hematological index is approximately an order of magnitude larger than the respiratory and systemic indices, while the neurotoxicity index is approximately three to four times larger. We therefore focus on these two neurological and hematological measures.

These indices measure modeled exposure relative to health-based reference levels. We aggregate them across nearby residential buildings to construct a well-level health-risk measure. Throughout, we use "health risk" as shorthand for hazard-index-weighted residential exposure. Specifically, 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). We normalize each building to have one resident; since all results are reported as percentage changes in aggregated health indices, the level of this normalization cancels out and is without loss of generality.

3 Empirical Evidence on the Permitting Channel

We document three observations about the effects of the regulation on permitting, investment, and the types of wells drilled. Observations 1 and 2 use synthetic diff-in-diff event studies [Arkhangelsky et al., 2021]; Observation 3 provides supplementary cross-sectional evidence on how grandfathered permits are used.

We compare Colorado, which is treated, to a synthetic untreated Colorado constructed from donor basins. We normalize each outcome by its own pre-period mean, then construct the synthetic counterfactual on the normalized series. The pre-period is 2012Q1–2017Q4; the anticipation period is 2018Q1–2018Q4; and the regulation period is 2019Q1–2019Q4.

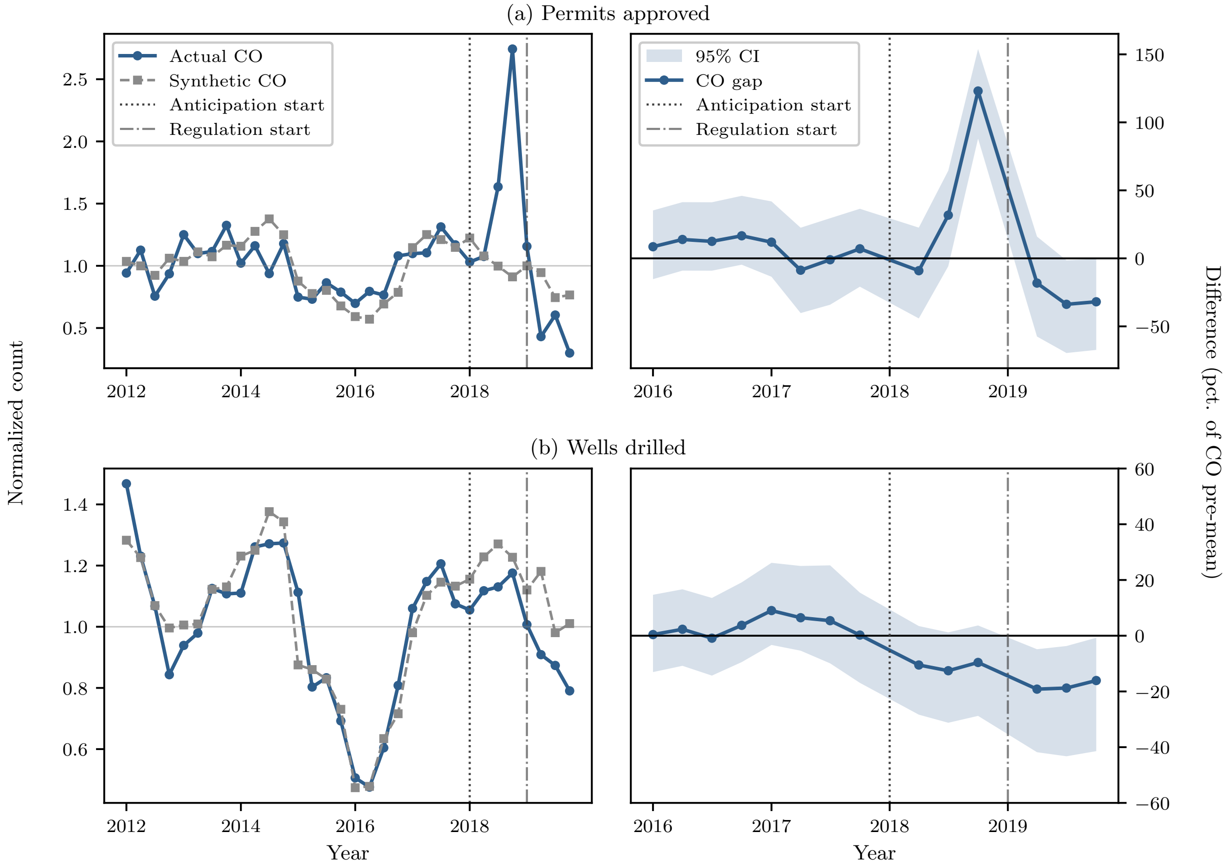
The key identifying assumption is that, absent the Colorado policy change, Colorado's outcomes would have continued to follow their synthetic counterfactual after 2017Q4. Parallel pre-trends provide the primary diagnostic for this assumption and Figure 2 presents this evidence. The left column shows Colorado and its synthetic counterfactual, while the right column plots the difference between the two series in the policy window. The close fit is particularly informative because the 2012Q1–2017Q4 pre-period spans six years and includes a boom and bust in drilling. Despite these fluctuations, the series track each other closely. Appendix Figure A.4 reports the same gaps over the full display window, and Table 2 reports the period estimates for the anticipation and regulation periods.

We provide three additional checks on the donor pool that support the key identifying assumption. First, we drop Oklahoma-dominated basins, since Oklahoma changed its induced-seismicity protocols during 2018 [Oklahoma Corporation Commission, 2018]. We obtain the same signs and main conclusions (Appendix Table A.3). Second, Colorado and synthetic Colorado match closely on pre-period covariates (Appendix Table A.5). The main imbalance is slightly lower average log oil production in synthetic Colorado, which reflects large gas donors whose wells produce little or no oil. Dropping gas-heavy donor basins yields broadly similar results (Appendix Table A.3). Third, we test an alternative donor-pool construction where we increase the minimum permits/drilled wells per quarter from 10 to 25 in Appendix Table A.3; the main conclusions are unchanged.[14]

One may also be concerned that the regulation displaces drilling to other states, raising activity in the synthetic diff-in-diff donor pool. For example, Vreugdenhil [2025] shows that drilling rigs can reallocate toward unregulated markets. However, such reallocation is unlikely to explain our results, since firms can increase permitting without reallocating rigs or drilling elsewhere.

[14] Recall that we make this data cleaning cut to avoid sparse/noisy donors.

Figure 2: Synthetic diff-in-diff fit and event-study differences



Note: Left panels plot Colorado and synthetic series, with each series normalized by its pre-period mean. Right panels plot the difference between Colorado and its synthetic counterfactual, measured as a percentage of Colorado's pre-period mean. Although the analysis uses data from 2012Q1 to 2019Q4, on the right panel we zoom in on the 2016Q1-2019Q4 period; Appendix Figure A.4 presents figure for the full window. Differences use a trailing two-quarter average that resets at the start of anticipation (2018Q1) and regulation (2019Q1). Vertical lines mark the start of anticipation and regulation. Shaded bands are pointwise 95% confidence intervals constructed using the conformal test-inversion procedure of Chernozhukov et al. [2021]. Table 2 reports period estimates.

Table 2: Synthetic diff-in-diff period estimates

	Anticipation (2018)		Regulation Period (2019)	
Outcome	$\hat{\tau}$ (%)	95% CI	$\hat{\tau}$ (%)	95% CI
Permits approved	+63.0	[+31.3, +81.6]	-19.0	[-52.4, +1.0]
Wells drilled	-11.4	[-24.4, -0.8]	-19.0	[-37.0, -7.8]

Note: Coefficients are full-Colorado synthetic diff-in-diff gaps, reported as percentages of Colorado's pre-period baseline. The treated unit pools all Colorado wells; donors are non-Colorado basin aggregates. We construct pointwise 95% confidence intervals using the conformal test-inversion procedure of Chernozhukov et al. [2021].

Observation 1: Permits surge before regulation.

Figure 2(a) shows that permit approvals increased dramatically in 2018 in anticipation of the policy change. The gap peaks in 2018Q4 (the last quarter before the new rules) and reverses once the regulation takes effect in 2019.

Table 2 reports the aggregate magnitudes. Over the anticipation period, permit approvals are 63.0% above the synthetic counterfactual, measured relative to the pre-period baseline. Firms also described this behavior directly. For example, one firm said that it "anticipat[es] having more than three years of drilling inventory permitted and 'ready to go' if the measure passes" [Traywick, 2018]. After the regulation takes effect, permits fall back to their mean, and then below the mean towards the end of 2019.[15].

Observation 2: Firms do not accelerate investment in anticipation of the regulation.

Figure 2(b) shows that drilling does not increase during the anticipation period. Similarly, Table 2 also provides no evidence of an increase in drilling. This is robust across alternative donor-pool specifications in Appendix Table A.3.[16] Furthermore, this divergence between drilling and the permitting spike in Observation 1 is consistent with permits serving as options. Specifically, 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 in 2019, Figure 2 shows a corresponding decrease in drilling. Much of the drilling that does occur in 2019 draws on the permits stockpiled before the regulation: 66% of Colorado wells drilled in 2019 used a grandfathered permit.

Note that grandfathered permits can affect not only the quantity of wells drilled but also

[15] Although the two-quarter event-study estimates ending in 2019Q3 and 2019Q4 are negative and significant at the 5 percent level, the full-year 2019 permit estimate is not statistically significant at the 5 percent level (Table 2). This has limited implications for our conclusions, since the key evidence consistent with the permitting channel is (i) the surge in permit approvals before regulation, and (ii) that this surge did not continue once the regulation was implemented.

[16] In fact, the aggregate percentage change in drilling in 2018 is negative and significant. This pattern suggests a disinvestment effect of regulation, which the model captures through anticipated compliance costs that reduce the value of drilling (Section 4).

the *type*: firms with grandfathered permits may drill closer to residential areas than firms obtaining permits under the new regulation. We turn to this idea in Observation 3.

Observation 3: Firms use grandfathered permits to drill wells closer to residential areas, with higher health risk.

We supplement the aggregate evidence in Observations 1 and 2 with a cross-sectional comparison of the wells drilled under grandfathered permits. The sample is Colorado wells drilled after the regulation takes effect (2019), when both grandfathered permits and permits awarded under the new regulation are in use. Table 3 compares wells using grandfathered permits to wells using regulation-period permits. Column (1) includes no geographic fixed effects, column (2) includes oil and gas basin and play fixed effects, and our preferred specification in column (3) adds county fixed effects while retaining the basin and play fixed effects.

Table 3 reports the results. 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). Within Colorado, wells using regulation-period permits are 34.2% less likely to be drilled within 1,500 feet of buildings than wells using grandfathered permits. They also have lower hematological and neurotoxicity exposure indices.

We measure hydrocarbon production as log(1 + BOE), where BOE stands for production in thousands of 'barrels of oil equivalent' (i.e., we convert any well natural gas production to equivalent barrels of oil).[17] In contrast to the health-risk measures, production does not significantly differ between grandfathered and non-grandfathered wells at the 5 percent level. Appendix Table A.6 shows the same conclusion when log(1 + BOE) is expressed in barrels rather than thousands of barrels and when production is instead measured by its dollar value, expressed in dollars or millions of dollars.

Appendix Table A.7 reports a placebo test where we perform the same empirical exercises that generate Table 3 but using Texas data, where regulation was relatively stable. In con-

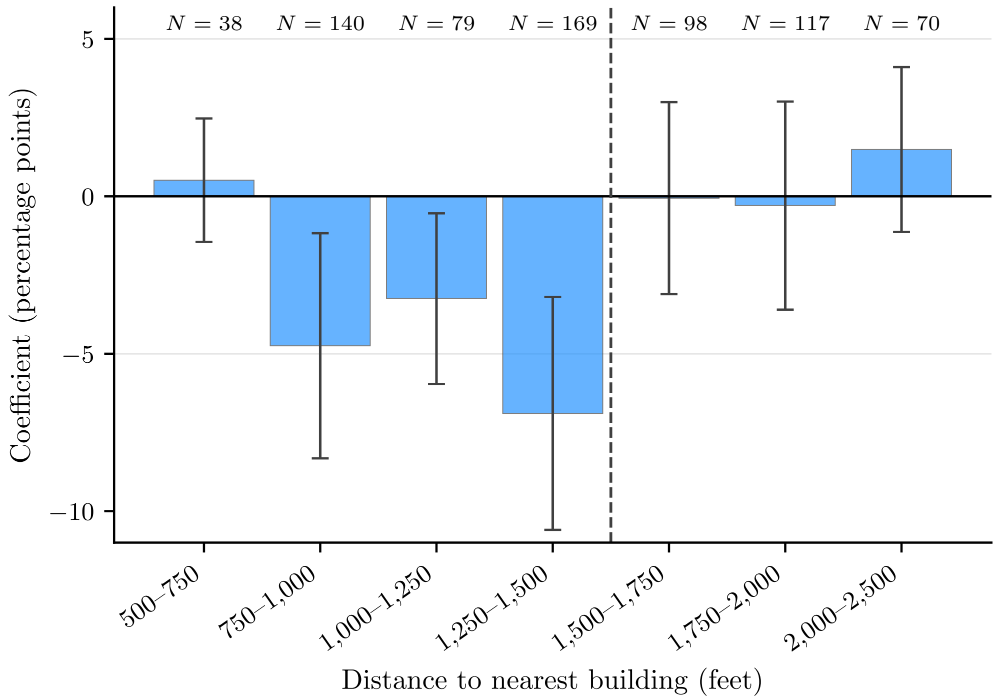
[17] We use a conversion factor of 5.8 thousand cubic feet of natural gas to 1 barrel of oil following [Kellogg, 2014]

Table 3: Grandfathered permits, location, and health exposure in Colorado

	(1)	(2)	(3)
Close to buildings (<1,500 ft)			
Estimate	-0.12	-0.16	-0.13
	(0.027)	(0.026)	(0.025)
Percent change vs. mean	-31.94	-43.72	-34.21
Hematological health-risk index			
Estimate	-0.074	-0.13	-0.11
	(0.029)	(0.027)	(0.027)
Percent change vs. mean	-15.65	-27.73	-23.35
Neurotoxicity health-risk index			
Estimate	-0.017	-0.029	-0.025
	(0.0065)	(0.006)	(0.006)
Percent change vs. mean	-16.15	-28.23	-23.68
Hydrocarbon production, $\log(1 + \text{BOE})$			
Estimate	0.094	0.04	-0.023
	(0.11)	(0.11)	(0.11)
Implied percent change	9.86	4.05	-2.25
Observations	1,308	1,308	1,308
Basin and play fixed effects	No	Yes	Yes
County fixed effects	No	No	Yes

Note: Sample is Colorado wells spudded in 2019. Estimates are coefficients on an indicator for whether the well uses a regulation-period permit rather than a grandfathered permit. Column (1) includes no geographic fixed effects, column (2) includes basin and play fixed effects, and column (3) adds county fixed effects while retaining the basin and play fixed effects. 'Close to buildings' equals one if the well is within 1,500 feet of a building. Health indices weight nearby residential buildings by distance-specific hazard indices from ICF [2019]. Hydrocarbon production is $\log(1 + \text{BOE})$, where BOE is measured in thousands of barrels of oil equivalent (details in the main text). The hydrocarbon percent row reports $\exp(\hat{\beta}) - 1$; other percent rows divide the coefficient by the grandfathered-permit mean.

Figure 3: Difference in drilling shares by distance to buildings



Note: The sample is Colorado wells drilled in 2019. The bars report coefficients from regressions of distance-bin indicators on an indicator for whether the well uses a regulation-period permit rather than a grandfathered permit, with fixed effects for each county–basin–play combination. Coefficients are reported in percentage points. Negative coefficients indicate that fewer wells are drilled under regulation-period permits than under grandfathered permits in the corresponding distance bin. Whiskers are 95% confidence intervals. The numbers above the bars report the number of wells in each bin. The vertical dashed line marks the 1,500-foot threshold.

trast to the corresponding Colorado estimates, the Texas placebo estimates for proximity and health exposure are small in magnitude and statistically indistinguishable from zero. This supports the interpretation that the Colorado patterns are driven by the change in regulation.

One may ask whether firms can comply with the 1,500-foot setback by moving the surface location just outside the threshold while still reaching the same reserves through horizontal drilling. Ericson et al. [2020] show that this technology can make moderate setback expansions less costly. In our setting, such relocation would imply fewer wells below the threshold and a compensating increase in the adjacent distance bands just above it. Figure 3 does not show that pattern. In this figure, a negative value indicates that fewer wells are drilled under regulation-period permits than under grandfathered permits in the corresponding distance bin. We see that the gap is concentrated below 1,500 feet and is approximately zero immediately above the threshold, i.e., there is no substitution slightly to the right of the 1,500-foot threshold. One explanation is leasing frictions: even when the same reservoir is technically reachable from a farther surface location, firms may not control the lease needed to drill from that location.

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. Waiting is valuable because it allows firms to take advantage of favorable shocks to prospect-specific conditions e.g., good information may arrive about the value of a specific prospect, or there may be lower local rig costs.[18]

Recall from Section 2.1 that firms anticipated an effective ban on drilling, but the realized regulation was more moderate. 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 has

[18]Another reason to wait is because oil and gas prices may rise in the future. However, during our simulation period 2017-2019, oil and gas prices were relatively stable (as compared to the crash in e.g., 2014-2016). Therefore, although the model could be extended to include this source of option value, in order to keep the model parsimonious, we abstract away from this channel.

a proximity type $\ell_i \in \{\text{far}, \text{close}\}$, indicating distance to occupied buildings.[19] We specify further how payoffs for each i depend on proximity type, along with our other assumptions on prospect heterogeneity, in Section 5. 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 takes effect at $t = T$. The model features three regimes described in Section 2.1: pre-anticipation, anticipation, and regulation. To simplify notation, we suppress time subscripts on γ in the value functions below, since each period's decision problem takes the prevailing belief as fixed. During the pre-anticipation period, firms do not expect regulation ($\gamma = 0$). During the regulation period ($t \geq T$), the regulation is in effect ($\gamma = 1$).

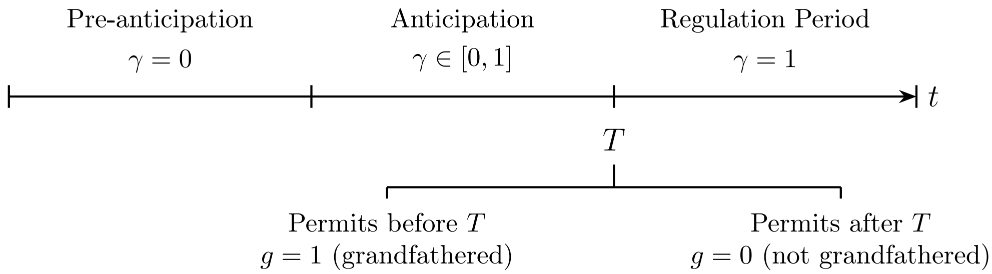
During the anticipation period, firms assign probability $\gamma \in [0, 1]$ to regulation taking effect at T. We allow this belief to vary across anticipation quarters and estimate its quarterly values (Section 5). For example, in 2018Q3, firms solve their dynamic problem holding the prevailing γ fixed over the remaining horizon and choose their current actions based on the resulting continuation values. When 2018Q4 arrives, we re-solve the problem using the separately estimated 2018Q4 belief. This specification allows beliefs to respond to new information as the regulation date approaches.

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 increases in permitting costs and restrictions; permits obtained after T have $g = 0$. Figure 4 summarizes this structure.

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

[19] Throughout the model and counterfactuals we refer to wells that are located close to buildings as "close wells".

Figure 4: Regulatory timeline and grandfathering.



Note: The timeline shows three regulatory regimes. During pre-anticipation, firms do not expect regulation ($\gamma = 0$). During anticipation, firms assign probability $\gamma \in [0, 1]$ to regulation taking effect at T. Note that in estimation γ is estimated separately for each anticipation period. In the regulation period, the regulatory regime is in effect ($\gamma = 1$). Permits obtained before T are grandfathered ($g = 1$) and exempt from additional close-well permitting costs.

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 unpermitted status.

Payoffs. Let $\pi_{i,r}$ denote the payoff from drilling prospect i under regulatory regime r, and let $c_{i,r}$ denote the cost of obtaining a permit under regulatory regime r. Regulation may affect $c_{i,r}$ if, for example, prospects i that are close wells cannot obtain permits under the new regulation. We also allow regulation to reduce $\pi_{i,r}$, which may capture expected costs of subsequent operating requirements, such as increased inspections and monitoring.[20] In the model, grandfathering protects firms against additional permitting costs while still leaving them exposed to changes in drilling payoffs. Section 5.1 explains these payoff changes, and 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. These shocks represent idiosyncratic prospect-specific conditions (as previously discussed at the start of this section) that make it valuable for firms to wait. Note that we allow for σ_{permit} and σ_{drill} to differ because firms may face different dispersions of the idiosyncratic shocks at

[20] As discussed in Section 2.1, firms may have interpreted a potential ballot passage as a signal that such requirements would become more likely.

the drilling versus permitting stage.

4.2 Value Functions and Choices

Pre-anticipation and regulation regimes. We first characterize value functions under a constant regulatory regime r. This formulation applies to the pre-anticipation regime and the regulation regime after T. To reduce the notational burden, we suppress the grandfathering state g from these value functions. Let $W_{i,r}$ denote the value of an unpermitted prospect i under regime r. The firm chooses between permitting and waiting.

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

where $\tau_{\max} = 7$ is the initial permit maturity, $c_{i,r}$ is the permit cost (which depends on proximity type ℓ_i and regime r), β is the quarterly discount factor, and $P_{i,r,\tau}$ is the value of holding a permit with maturity τ.[21] For a permitted prospect with maturity $\tau > 0$:

$$P_{i,r,\tau} = \mathbb{E}_{\varepsilon} \max \Big\{ \underbrace{\pi_{i,r} + \sigma_{\text{drill}}\varepsilon_{i,3}}_{\text{drill}}, \quad \underbrace{\beta P_{i,r,\tau-1} + \sigma_{\text{drill}}\varepsilon_{i,4}}_{\text{let permit age}} \Big\} \tag{2}$$

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 $c_{i,\text{pre}}$. We denote anticipation value functions with γ as a regime subscript and time t as the final subscript.

[21] 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 $\tau = 0$.

Period $t = T-1$: Firms learn next period whether the regulation arrives. 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. 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:

$$W_{i,\gamma,T-1} = \mathbb{E}_\varepsilon \max \Big\{ \underbrace{-c_{i,\text{pre}} + P_{i,\gamma,\tau_{\max},T-1} + \sigma_{\text{permit}}\varepsilon_{i,1}}_{\text{permit}}, \quad \underbrace{\beta\big[(1-\gamma)W_{i,\text{pre}} + \gamma\hat{W}_{i,\text{post}}\big] + \sigma_{\text{permit}}\varepsilon_{i,2}}_{\text{wait}} \Big\} \tag{3}$$

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

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

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

Period $t = T-2$ and earlier: For $t < T-1$, the recursive structure continues. Continuation values for waiting and aging point to the next period's value functions, e.g., the $T-2$ value functions use the $T-1$ value functions in the next period. We solve these cases by backward 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. This includes firms holding grandfathered permits, who choose whether to drill in each period given these parameters.

4.3 Aggregation and Simulation

Given the parameters, we aggregate up individual decisions to a market-level response. To do so we solve and simulate the model separately for each prospect type over 12 quarters from 2017 through 2019, starting from long-run permit stocks computed using the pre-anticipation parameters.[22] The next section specifies these prospect types and their distribution. 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. Computational details are in Appendix A.2.

5 Identification and Estimation

5.1 Overview

Payoff structure and types. 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. We define q as the production value of a well, measured using gross revenue during its first 36 months of production. The drilling payoff is q minus drilling cost c_{drill} and any regime-specific regulatory costs.

We assume that all prospects share a common production value q. This implies that proximity type is the only source of observable prospect-level heterogeneity in the model. We denote the latent share of close-type prospects as s_{close}.[23] Although we could extend the model to capture additional observable heterogeneity in q, we choose not to do so because this extension is unlikely to have a first-order effect on our results. Specifically, a common q could be problematic if proximity to buildings were correlated with hydrocarbon production, because regulation would then alter the productivity mix of drilled wells. However, Table 3 shows no significant difference in production between wells drilled under grandfathered and non-grandfathered permits, suggesting that this concern is limited.[24]

Prior to regulation, we assume that 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 $c_{i,r} = \infty$.[25]

[22] Although the synthetic diff-in-diff pre-period begins in 2012, for simplicity we compute the pre-anticipation period using only the four quarters of 2017.

[23] Recall that the model still allows for idiosyncratic differences in profitability across prospects through the shocks.

[24] Furthermore, oil and gas prices were relatively stable from 2017 to 2019, supporting the assumption of constant q across time.

[25] Recall that the 2018 ballot initiative (Proposition 112) proposed 2,500-foot setbacks from occupied

Table 4: Payoff structure and calibrated parameters

(a) Payoff structure by regime

Regime	Drilling payoff $\pi_{i,r}$	Permit cost $c_{i,r}$
Pre-anticipation	$q - c_{\text{drill}}$	c
Regulation (anticipated)	$q - c_{\text{drill}} - \hat{q}$	∞
Regulation (realized), $g = 0$	$q - c_{\text{drill}} - \tilde{q}$	c (far) or $c + \tilde{c}_{\text{close}}$ (close)
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)	0.002
c_{drill}	Drilling cost (\$M)	6.0
q	Production value (\$M)	7.7

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. Firms drilling on grandfathered permits ($g = 1$) do not pay the close-well regulatory cost $\tilde{c}_{\text{close}}$ (which is charged when firms acquire permits). Panel (b) reports externally calibrated parameters; sources are discussed in the text.

Although the ballot initiative focused on setbacks, which correspond to drilling location, we flexibly allow anticipated regulation to reduce drilling payoffs even after a well is drilled in a specific location. We denote the reduction in drilling value conditional on regulation taking effect by $\hat{q}$, so the anticipated regulation-period payoff is $q - c_{\text{drill}} - \hat{q}$. As discussed in Section 2.1, firms may have viewed passage as a signal that subsequent operating requirements would become more likely. Under this interpretation, $\hat{q}$ captures the expected cost of these subsequent requirements, including for wells drilled under grandfathered permits.

As discussed in Section 2.1, the realized regulation was more moderate, imposing additional requirements primarily for wells near occupied buildings. A grandfathered permit protects firms against the additional close-well permitting cost $\tilde{c}_{\text{close}}$. We also allow for a realized reduction in drilling value, $\tilde{q}$ (which can differ from $\hat{q}$). We estimate these reductions from firms' permitting and drilling responses, as discussed in Section 5.2.

buildings (and "vulnerable areas" such as waterways and reservoirs), which would have affected most drilling locations in Colorado.

Anticipation beliefs. During 2017, firms had no reason to expect regulatory change ($\gamma = 0$). The synthetic diff-in-diff event-study gaps in Figure 2 show that the permit response is concentrated in 2018Q3–Q4, so we calibrate $\gamma = 0$ for 2018Q1 and 2018Q2 as well.[26] We estimate $\gamma = \gamma_{\text{Q3}}$ for 2018Q3 and $\gamma = \gamma_{\text{Q4}}$ for 2018Q4, allowing beliefs to change about the success of the ballot initiative in the approach to the 2018Q4 election.

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.[27] We assume a permit cost of $c = \$2{,}000$.[28] The production value $q = \$7.70$ million equals average gross revenue during the first 36 months of production for Colorado wells in our sample during the model's pre-anticipation period (2017).[29] As we show in Appendix Table A.2, counterfactual results are robust to alternative assumptions on the calibrated parameters.

5.2 Identification

We target nine empirical moments, several constructed from the event-study estimates in Section 3. We group the identification arguments into three parts.

Permit and drilling choice-shock parameters. The parameter σ_{drill} governs how drilling is distributed across each permit's life. The moment for the share of wells drilled within one year of permit approval pins down this parameter. Lower σ_{drill} concentrates drilling in the first few quarters, while higher σ_{drill} spreads it out more evenly.

[26] In principle, these could be estimated, but the event-study estimates are indistinguishable from zero in these quarters. Therefore, calibrating these parameters directly simplifies estimation and is unlikely to affect our results.

[27] The EIA reports annual nominal drilling and equipping costs per foot by well type through 2007 [U.S. Energy Information Administration, 2007]. We take each crude oil well value from 2002–2007, adjust for inflation, and average across years, yielding approximately \$457 per foot. Multiplying average cost per foot by average measured depth for Colorado wells in 2017 yields approximately \$6.0 million.

[28] We use the eight-hour paperwork burden estimated for federal permit applications as a benchmark [Bureau of Land Management, 2015] since Colorado applications for nonvertical wells require similar well-location information and drilling plans [Colorado Oil and Gas Conservation Commission, 2014]. We value preparation time at an assumed \$300/hour, approximately the average Colorado attorney rate [Clio, 2024], yielding \$2,400, which we round to \$2,000.

[29] We compute revenue from Enverus production data, valuing oil at the average 2018 WTI price and gas at the average 2018 Henry Hub price. These prices were relatively stable during the 2017–2019 simulation period, as compared to e.g., the earlier 2012-2016 period.

The corresponding permitting choice-shock parameter σ_{permit} is harder to pin down directly, since we observe counts of approved permits but not the full stock of latent prospects deciding whether to apply. In the model, the firm owning each prospect in this stock chooses between acquiring a permit and waiting. We therefore discipline σ_{permit} using the 2019H2 permit response from the event study, which compares permits acquired in the second half of 2019 to the pre-anticipation period. This moment captures how permitting changes when permit values fall. Intuitively, lower values of σ_{permit} make permit choices more sensitive to additional regulatory costs, moving the 2019H2 response farther below zero. Conversely, higher values make permit choices less sensitive to changes in payoffs, moving the response toward zero.

Realized regulatory costs and latent well types. Recall that the parameter $\tilde{q}$ denotes the realized regulatory cost, i.e., the reduction in drilling value that applies to all wells after regulation. We identify this parameter using the average drilling response in the first half of 2019 and an indicator for whether drilling fell from 2018Q4 to 2019Q1.[30]

We identify the parameter s_{close} using the share of wells drilled near buildings over the 2017–2019 model window. Recall that the parameter $\tilde{c}_{\text{close}}$ is the additional cost of permitting wells close to buildings under the realized regulation, which firms holding grandfathered permits do not pay. We identify this parameter using a moment that leverages Observation 3 in the descriptive evidence: the difference between the close-well shares of wells drilled under grandfathered and non-grandfathered permits.

Anticipation parameters. With σ_{drill}, σ_{permit}, s_{close}, $\tilde{q}$, and $\tilde{c}_{\text{close}}$, identified from the moments above, the remaining anticipation parameters — beliefs γ_{Q3} and γ_{Q4}, and anticipated regulatory cost $\hat{q}$ — are disciplined by three anticipation moments. The permit event-study responses in 2018Q3 and 2018Q4 (Observation 1) discipline the timing of beliefs as the election approached. The corresponding drilling response (the absence of any anticipation-period

[30]We target the first half of 2019, before the stock of grandfathered permits acquired during anticipation is depleted. The indicator rules out a drilling rebound when the regulation took effect. The regulation-period 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.

drilling increase documented in Observation 2, despite the permit surge) disciplines the anticipated regulatory cost $\hat{q}$. 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): $\hat{\theta} = \arg\min_\theta [m(\theta) - \hat{m}]' W [m(\theta) - \hat{m}]$, where θ is the parameter vector, $m(\theta)$ is the vector of model-predicted moments, $\hat{m}$ is the vector of empirical moments, and W is a diagonal weighting matrix.

Table A.1 in Appendix A.3 compares the targeted moments to their model counterparts. The model fits the data well. In particular, it captures the sharp increase in permits and the absence of an increase in drilling during anticipation. Table 5 reports the estimates.

Firms formed their beliefs about regulation gradually. We estimate that in 2018Q3 firms assigned probability $\gamma_{\text{Q3}} = 0.17$ to the regulation taking effect, rising to $\gamma_{\text{Q4}} = 0.40$ by 2018Q4 as the election approached. We also find that drilling decisions are more precise ($\sigma_{\text{drill}} = 0.22$) than permitting decisions ($\sigma_{\text{permit}} = 0.31$). 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 anticipated a stricter regulation than the one ultimately implemented. Concretely, the estimated loss in drilling value under the anticipated regulation is $\hat{q} = \$3.78$ million, while the realized regulation imposes $\tilde{q} = \$0.27$ million for all wells.

This over-anticipation drives the permit surge documented in Section 3. Firms stockpile grandfathered permits against an anticipated regulation that would prevent new permit issuance and thereby halt future drilling of unpermitted prospects. When the weaker regulation was implemented, these permits became most valuable for close wells because they allowed firms to bypass the close-well regulatory cost $\tilde{c}_{\text{close}}$. 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.

Table 5: Estimated parameters

Parameter	Description	Estimate	Std. error
σ_{permit}	Choice dispersion (permit)	0.31	(0.03)
σ_{drill}	Choice dispersion (drill)	0.22	(0.03)
s_{close}	Share of close prospects	0.19	(0.06)
γ_{Q3}	Anticipation belief (2018Q3)	0.17	(0.06)
γ_{Q4}	Anticipation belief (2018Q4)	0.40	(0.03)
$\hat{q}$	Anticipated regulatory cost ($M)	3.78	(0.16)
$\tilde{q}$	Realized regulatory cost ($M)	0.27	(0.12)
$\tilde{c}_{\text{close}}$	Close-well regulatory cost ($M)	0.40	(0.20)

Note: SMM estimates; standard errors in parentheses, computed across 200 bootstrap replications.

6 Counterfactuals

6.1 Overview

We use the estimated model to quantify the effects of policy designs that remove the permitting channel on health risk and oil and gas production. Starting from the implemented regulation, we simulate counterfactual policies that sequentially remove grandfathering and then anticipation. Without grandfathering, all regulation-period drilling faces the regulatory cost regardless of when the permit was acquired. Removing grandfathering therefore isolates the effects of the permitting channel. Under surprise regulation, firms receive no advance warning, and regulation arrives unexpectedly in 2019Q1.

We map each well's type, either close to or far from buildings, into a health-risk weight.[31]

[31] Recall from Section 2.2 that we construct two well-level health exposure measures using a concentric ring analysis, one based on the hematological hazard index and one based on the neurotoxicity hazard index. For each permitted well, we count residential buildings within 16 distance bands from 0–150 feet to 1,800–2,000 feet (Figure A.2) and weight each building by the relevant acute non-cancer hazard index at its distance (Figure A.3; ICF [2019]).

Specifically, we use mean hematological exposure among wells of each type drilled in 2017.[32] This yields health weights of 1.26 and 0.11 for close and far wells, respectively. Since these weights come from an index, we report all results as percentage changes, which do not depend on the index's scale.

As mentioned in Section 2.1, we report health risk and oil and gas production separately rather than aggregating them into a single welfare number, because the welfare weights are politically contested in our setting. Regardless of these weights, our results illustrate that the permitting channel is important and our framework can be used to determine what any policy design delivers on both margins.

6.2 Results

Table 6 reports the counterfactual results, and Figure 5 shows the dynamics of permits and drilling under each scenario. We report all changes relative to the implemented regulation. In the Health-Risk Improvement column, positive values indicate decreases in health risk. We also report the change in oil and gas production. The remaining columns report percentage changes in permits and drilling.

First, we eliminate grandfathering, which implies that permit timing no longer determines which wells the new regulation covers. This reflects the design of many other real-world policies, such as Title V air permits, which may be reopened when new requirements are implemented [U.S. Environmental Protection Agency, 2026, 40 C.F.R. § 70.7(f)]. Table 6 shows that this policy reduces health risk by 28%. This total combines two opposing effects.

The first effect is the loss of the regulatory shield for grandfathered permits exercised in the regulation period. Under the implemented policy, grandfathered permits account for 80% of health risk during the first year of regulation. Once these permits no longer preserve favorable regulatory treatment, regulation-period drilling falls by 42%. This decline generates the main health-risk improvement.

[32] Recall that we focus on two health-risk measures: one based on the hematological hazard index and one based on the neurotoxicity hazard index. The measures are highly correlated because both vary primarily with distance from buildings. Using the neurotoxicity-based exposure measure instead produces nearly identical percentage changes and leaves the qualitative conclusions unchanged.

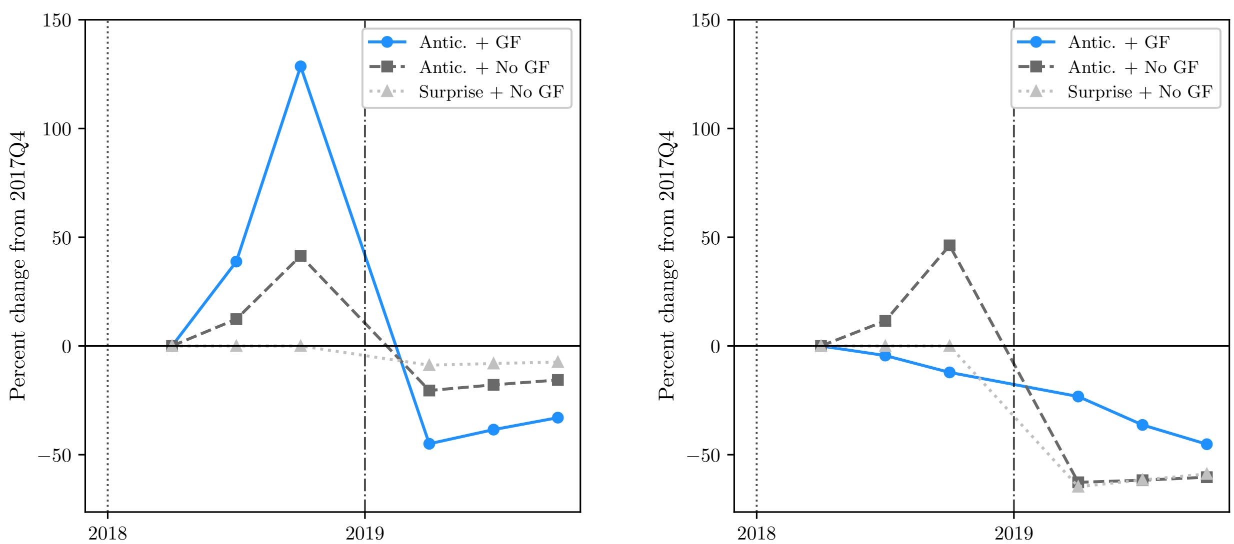
Table 6: Health-risk and production effects of alternative policy designs

Policy Design	Health-Risk Improvement	Oil and Gas Production	Anticipation Period		Regulation Period
			Permits	Drilling	Drilling
Change from baseline:					
Remove grandfathering	+28%	+1%	-27%	+31%	-42%
Also remove anticipation	+8%	-15%	-13%	-25%	0%
= Total change	+36%	-13%	-39%	+6%	-42%

Note: Health-risk improvement is the percent reduction in hazard-index-weighted residential exposure relative to the implemented regulation. Positive values indicate lower health risk.

Figure 5: Counterfactual permit and drilling dynamics

(a) Permits (b) Drilling



Note: Percent change relative to 2017Q4. The series show trailing two-quarter averages that reset at the start of anticipation and regulation, consistent with the event studies in the descriptive evidence section. This construction yields three plotted points in each regime. Vertical lines indicate referendum announcement (2018Q1) and regulation start (2019Q1).

The second effect is anticipatory drilling. Firms can no longer avoid the new rules by obtaining a relatively inexpensive permit and waiting to drill. However, firms can instead drill before the regulation takes effect and partially avoid the regulation. Anticipation-period drilling consequently rises by 31%, offsetting part of the regulation-period health-risk improvement.

Figure 5 shows how activity shifts across the two periods. Panel (a) shows that removing grandfathering reduces the anticipatory permit surge. Panel (b) shows that some drilling moves into the anticipation period, while regulation-period drilling falls sharply. With grandfathering, permits move forward while drilling does not; without grandfathering, some drilling also moves forward. In other words, removing grandfathering induces the anticipatory drilling response emphasized by Green Paradox models, but actually reduces health risk relative to the baseline implemented policy.

The Oil and Gas Production column shows that production actually rises 1%, compared to the 28% health-risk improvement. One interpretation is that eliminating grandfathering causes oil and gas companies to reallocate drilling from close wells to wells farther from buildings. This reallocation may appear surprising because neither the market nor the model explicitly links the two well types. Instead, the result reflects two features of the setting: the implemented regulation has heterogeneous effects on the two well types, and it was weaker than the regulation that firms anticipated.

To explain the above result further, consider first the wells that are far from buildings. Since firms anticipate a regulation that would make new permitting impossible and thereby halt future drilling of unpermitted prospects, they substantially speed up drilling before the regulation when grandfathering is eliminated. When the weaker regulation arrives, firms reduce drilling, but not as much as they anticipated, so the wells drilled early are not offset by lower drilling later. Eliminating grandfathering therefore spurs an overall increase in these far wells. Firms also speed up drilling of close wells in anticipation. But since these wells are subject to the more stringent implemented regulation in 2019, firms reduce drilling of close wells over the full window. The cumulative total of these effects is that drilling (and with it oil and gas production) remains relatively stable, while the policy improves health risk because fewer close wells and more far wells are drilled.

Second, we remove anticipation through a 'surprise regulation,' which yields an additional 8 percentage-point health-risk improvement. Without advance warning, firms cannot stockpile permits or accelerate drilling before regulation takes effect. Panel (a) of Figure 5 shows the permit surge concentrated in the anticipation window; removing anticipation eliminates this channel. In total, removing both grandfathering and anticipation reduces health risk by 36% and oil and gas production by 13%.

Summary and robustness These comparisons use the 2019 regulation-period window, consistent with the empirical analysis, which ends before the COVID-19 shock. However, permits remain valid for two years, so part of the grandfathered stock is still active when the window closes. We address this in Appendix Table A.8, where we extend the simulation — holding the estimated regulation-period environment fixed — through 2020Q4, by which point the grandfathered permit stock is exhausted. The results are qualitatively similar: over the longer window, removing grandfathering improves health risk by 22%.

As we show in Appendix Table A.2, these results are robust to alternative assumptions on the calibrated parameters. We also rebuild the empirical moments and re-estimate the model using the alternative synthetic diff-in-diff donor pools discussed in Section 3, because the resulting estimates enter the targeted moments (Appendix Table A.4). The qualitative conclusions are unchanged across donor pools.

Overall, the permitting channel is a significant source of regulatory leakage. Grandfathered permits shield firms from regulatory costs, which generates stockpiling and intertemporal leakage. Our model illustrates that eliminating grandfathering would capture a substantial proportion of the achievable health-risk improvement, even when firms anticipate the regulation. Furthermore, removing grandfathering delivers most of the health-risk improvement with a modest change in production, while removing anticipation adds a smaller health-risk improvement at the cost of lower production.

7 The permitting channel in other markets

The permitting channel can potentially occur when (i) firms hold real options that can shield them from regulation, and (ii) these firms have advance notice of the regulation. In this section, we document the permitting channel more broadly across oil and gas markets beyond Colorado, as well as housing and electricity markets. Although these settings differ in the regulation at stake and the type of permit involved, each satisfies these two preconditions. In each setting, we document that permits surge in anticipation of regulation while investment remains stable.

Oil and gas markets California's 2024 setback regulation satisfies the two conditions. The regulation restricted new permits for drilling near occupied buildings and grandfathered existing approvals [CalGEM, 2024].[33] Subfigure 6a 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 6b shows an analogous pattern in federal oil and gas permitting ahead of Biden's announced freeze on new permits.[34] The proposed ban targeted new permits, firms had advance notice from the 2019 campaign announcement, and existing permits would be exempt. Permits on federal land spiked in the lead-up to January 2021 while drilling remained stable. In Appendix D.2, we compare both permit series with Texas permit approvals, which remain stable during the corresponding episodes. This indicates that aggregate shocks to oil and gas prices are unlikely to be an explanation for the observed spikes.

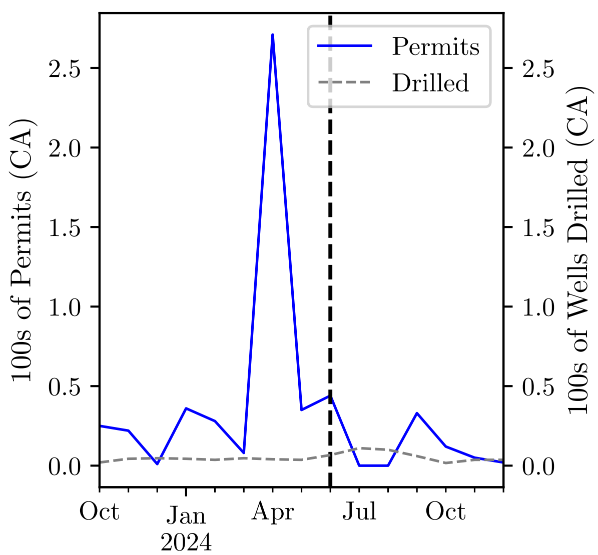
Housing markets The permitting channel extends beyond energy markets. For example, New York City's '421-a' program provided a partial property tax exemption for new multifamily housing construction. When the program faced expiration in June 2015, build-

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

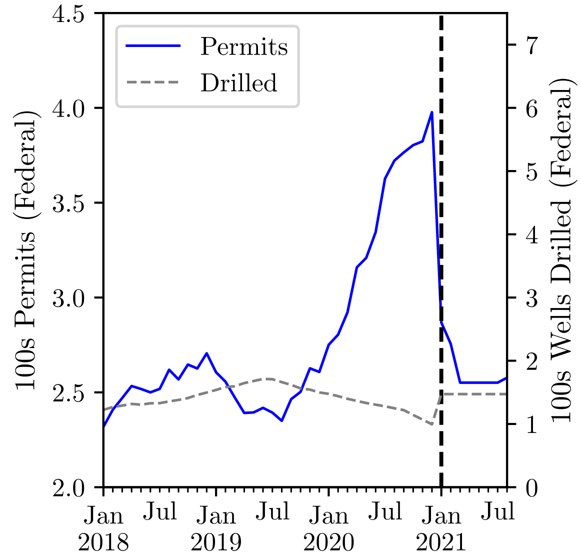
[34]The freeze was part of Biden's climate plan, announced in June 2019 [Biden for President Campaign, 2019].

Figure 6: 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 a rolling average of the number of federal wells spudded. In both panels, permits spike in anticipation of regulation while drilling activity remains stable.

ing permits filed before the deadline locked in the existing tax treatment for the life of the project [NYU Furman Center, 2015]. Figure A.6 (Appendix) shows that the city authorized a substantial spike in residential units in Q2 2015. 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. In 2021, the central government announced plans to control coal-fired power capacity and to phase down coal consumption during 2026–2030 [National Development and Reform Commission, 2021, para. 11]. This caused developers and officials to treat the period through 2025 as a "policy window" for new coal power plants: "This is causing a rush to secure permits for new projects" [Centre for Research on Energy and Clean Air, 2024]. These approvals did not all translate into immediate construction, consistent with them serving as real options. Indeed, observers noted that developers in some provinces might be securing permits "just in case" while delaying construction [Centre for Research on Energy and Clean Air, 2023].[35]

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. Using Colorado's 2019 oil and gas reforms, we document that 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. This is in contrast to the conventional Green Paradox response, in which firms accelerate physical investment *ahead* of regulation. Our structural estimates confirm that removing the permitting channel reduces health risk by 28%, with modest changes to oil and gas production, despite amplifying anticipatory investment. Removing both grandfathering and

[35] 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].

anticipation reduces health risk by 36% and oil and gas production by 13%.

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 has implications for testing for regulatory leakage due to anticipatory effects: when real options 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, and Section A.2 describes the simulation algorithm.

A.1 Computation

A.1.1 Steady state regimes

The model requires computing three steady-state value functions: pre-anticipation, anticipated regulation, and the realized regulation. Note that by "anticipated regulation" we mean the value functions for a firm in 2019 had the stricter regulation that firms anticipated in 2018 been implemented; we require this to compute firms' decisions leading up to the regulation being implemented in 2019Q1.

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 $\tau = 0$:

$$\bar{P}_{i,r,0}^{(n)} = \sigma_{\text{drill}} \cdot \log\left(\exp\left(\frac{\pi_{i,r}}{\sigma_{\text{drill}}}\right) + \exp\left(\frac{\beta \bar{W}_{i,r}^{(n)}}{\sigma_{\text{drill}}}\right)\right) + \sigma_{\text{drill}}\gamma^{\text{euler}} \tag{5}$$

For $\tau > 0$:

$$\bar{P}_{i,r,\tau}^{(n)} = \sigma_{\text{drill}} \cdot \log\left(\exp\left(\frac{\pi_{i,r}}{\sigma_{\text{drill}}}\right) + \exp\left(\frac{\beta \bar{P}_{i,r,\tau-1}^{(n)}}{\sigma_{\text{drill}}}\right)\right) + \sigma_{\text{drill}}\gamma^{\text{euler}} \tag{6}$$

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:

$$\bar{W}_{i,r}^{(n+1)} = \sigma_{\text{permit}} \cdot \log\left(\exp\left(\frac{-c_{i,r} + \bar{P}_{i,r,\tau_{\max}}^{(n)}}{\sigma_{\text{permit}}}\right) + \exp\left(\frac{\beta \bar{W}_{i,r}^{(n)}}{\sigma_{\text{permit}}}\right)\right) + \sigma_{\text{permit}}\gamma^{\text{euler}} \quad (7)$$

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.

A.1.2 Anticipation regime via backwards induction

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 Simulation Algorithm

We simulate drilling and permitting behavior forward in time, taking the computed steady states and choice probabilities as inputs. This aggregates up individual choice behavior to market-level dynamics.

State variables The simulation tracks two objects:

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

Initialization At the start of the simulation, we must initialize how prospects are distributed between the unpermitted state and outstanding permits of different remaining maturities. We construct this distribution using pre-anticipation permitting choice probabilities. Specifically, for this initialization, we ignore drilling and compute the stationary distribution generated as firms acquire permits, permits age, and unexercised permits expire. This calculation produces an initial distribution of prospects with and without permits and, among permitted prospects, across remaining permit maturities. All initial permits have $g = 1$ because they were issued before regulation.

Period-by-period transitions We first use the value functions to compute choice probabilities for every period and state. We then simulate stocks forward using three steps in each period t:

1. *Permit acquisitions*: For each unpermitted prospect, the firm chooses whether to obtain a permit:

$$\text{NewPermits}_t(\ell) = N_t^U(\ell) \cdot \Pr(\text{permit} \mid \ell, t). \tag{8}$$

   Let g_t denote the grandfathering status assigned to permits issued in period t: $g_t = 1$ for $t < T$ and $g_t = 0$ for $t \geq T$.

2. *Drilling and waiting*: Newly permitted prospects enter at $\tau = 7$, and firms immediately choose whether to drill them or wait. Existing permit holders make the same choice at their current maturity. The resulting drilling flows are:

$$\text{ImmediateDrills}_t(\ell) = \text{NewPermits}_t(\ell) \cdot \Pr(\text{drill} \mid \ell, 7, g_t, t), \tag{9}$$

$$\text{Drills}_t(\ell, \tau, g) = N_t^P(\ell, \tau, g) \cdot \Pr(\text{drill} \mid \ell, \tau, g, t). \tag{10}$$

3. *Update stocks*: Drilled prospects exit. Unpermitted prospects whose firms wait remain unpermitted, while permits left unexercised at $\tau = 0$ expire and return to the unpermitted state. Existing permits at higher maturities age by one quarter, and newly

issued permits left unexercised enter the next quarter at $\tau = 6$:

$$N_{t+1}^{U}(\ell) = N_t^{U}(\ell) \cdot \Pr(\text{wait} \mid \ell, t) + \sum_g N_t^{P}(\ell, 0, g) \cdot \Pr(\text{wait} \mid \ell, 0, g, t), \tag{11}$$

$$N_{t+1}^{P}(\ell, \tau, g) = N_t^{P}(\ell, \tau+1, g) \cdot \Pr(\text{wait} \mid \ell, \tau+1, g, t), \qquad \tau \in \{0, \ldots, 5\}, \tag{12}$$

$$N_{t+1}^{P}(\ell, 6, g_t) = \text{NewPermits}_t(\ell) \cdot \Pr(\text{wait} \mid \ell, 7, g_t, t). \tag{13}$$

Aggregation Total drilling in period t is:

$$\text{TotalDrills}_t = \sum_{\ell} \left(\text{ImmediateDrills}_t(\ell) + \sum_{\tau, g} \text{Drills}_t(\ell, \tau, g) \right) \tag{14}$$

A.3 Model Fit

Table A.1: Model fit: Empirical vs. simulated moments

Moment	Empirical	Simulated
Permit approvals		
Permits % change (2018 Q2–Q3)	+37.8%	+38.8%
Permits % change (2018 Q3–Q4)	+129.0%	+128.6%
Permits % change (2019H2)	-25.9%	-33.0%
Drilling rates		
Drilling % change (2018 anticipation avg.)	-12.4%	-8.3%
Drilling % change (2019 Q1–Q2)	-20.5%	-23.2%
Drilling falls 2018Q4 → 2019Q1 (indicator)	Yes	Yes
Grandfathering effects		
Close-well share change (g=0 vs g=1)	-34.2%	-31.8%
Drilling composition		
Close drilling share (2017–2019)	36.9%	28.9%
Pre-anticipation behavior		
Prob. drill in first year	81.7%	82.7%

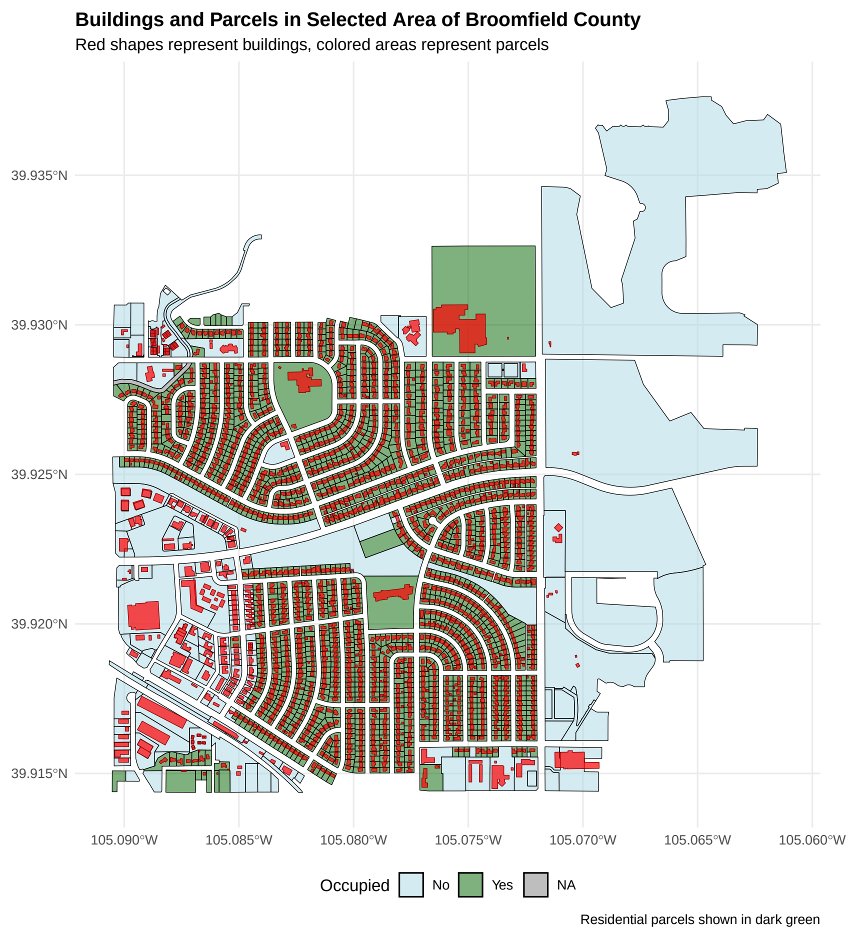
Note: Event-study moments are percent changes relative to the pre-period baseline (the 2017 average for permits, 2017Q4 for drilling). The 2018 anticipation moments use trailing two-quarter windows ending in 2018Q3 and 2018Q4, labeled by the quarters they span; the drilling anticipation moment is the average of the two windows. The 2019 permit moment averages 2019Q3–Q4 and the 2019 drilling moment averages 2019Q1–Q2. The close-share difference compares wells drilled on regulation-period permits to wells drilled on grandfathered permits (Observation 3). The realization-step moment is an indicator that drilling fell from 2018Q4 to 2019Q1. Overall, the model fits the moments well.

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 A.1 illustrates the classification for a sample area. We calculate distances between wells and nearby buildings using the NAD83 / UTM Zone 13N coordinate system.

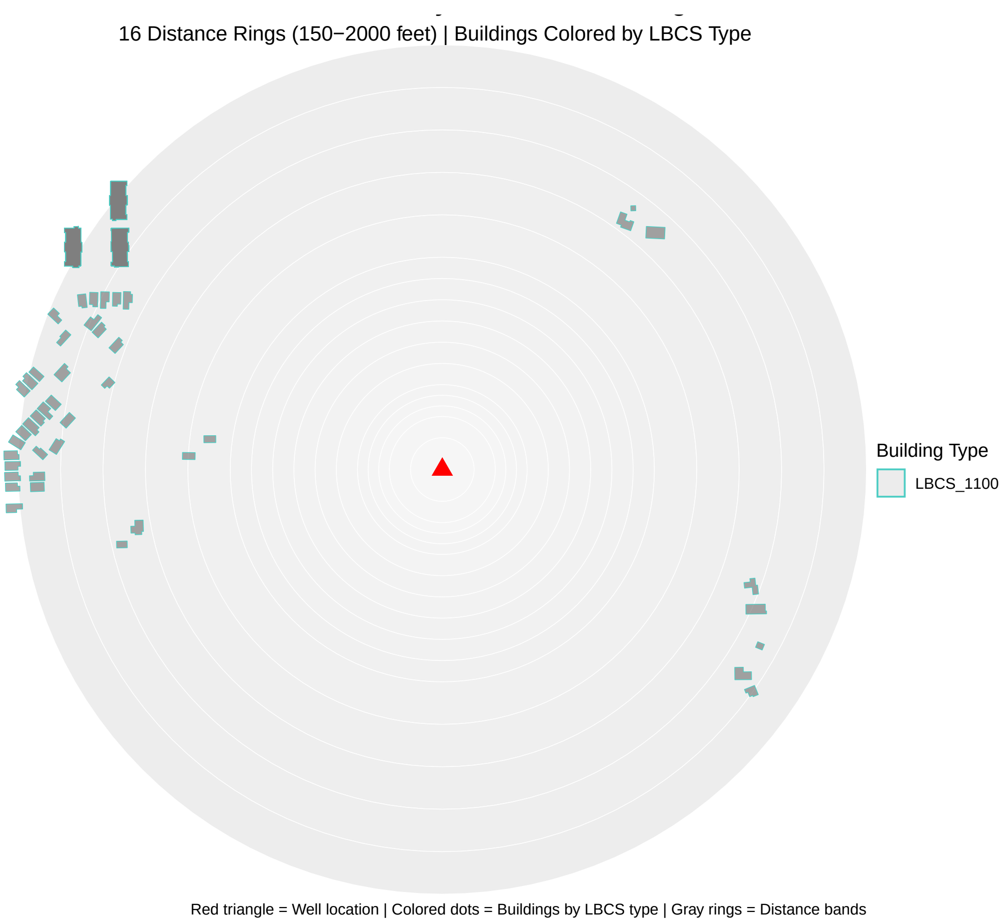
Concentric ring analysis We conduct a 'donut' analysis that counts buildings within concentric distance rings around each well location. We define 16 distance bands ranging from 0–150 feet (Ring 1) to 1,800–2,000 feet (Ring 16), with finer resolution at closer distances where health impacts are largest. 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 A.2 shows an example for a single well, and Figure A.3 plots the health hazard indices by distance.

Figure A.1: Occupied parcels in Broomfield



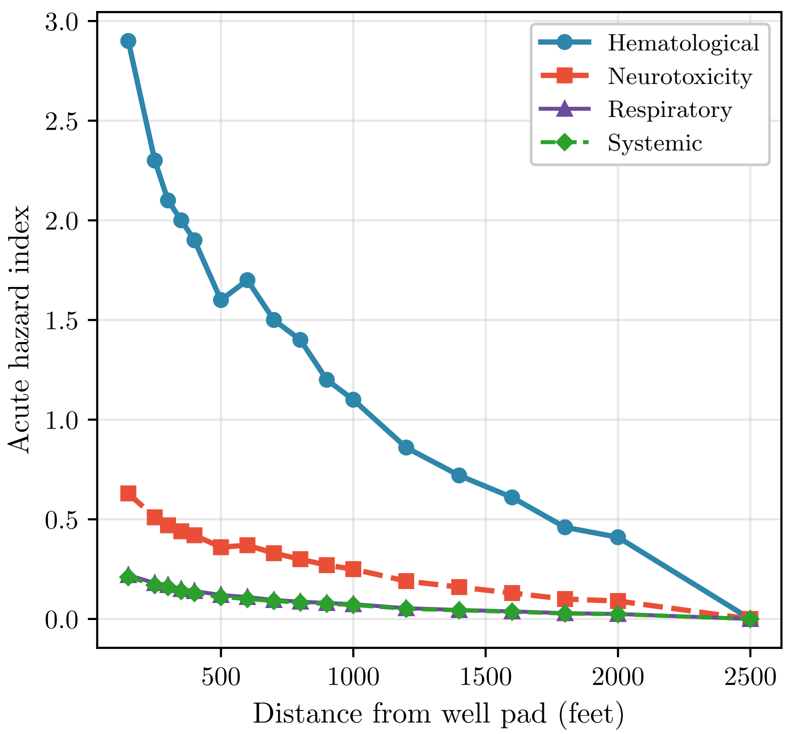
Note: Example of building classification in Broomfield County, Colorado. Residential parcels (classified using LBCS codes) are shown in color. Building footprints from Microsoft US Building Footprints are matched to parcel data from Regrid to determine occupancy status.

Figure A.2: Distribution of buildings around a particular well in our data



Note: Example of concentric ring analysis for a single well. Each band 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 A.3: 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 Additional Tables

Table A.2: Sensitivity of counterfactual results to calibrated parameters

	Benchmark	$\pi \times 2$	$\pi \times 0.5$	$c \times 0.5$	$c \times 2$
Health-risk improvement:					
Remove grandfathering	+27.83%	+19.30%	+27.84%	+27.82%	+27.86%
Also remove anticipation	+8.13%	+12.19%	+8.12%	+8.16%	+8.06%
= Total change	+35.96%	+31.49%	+35.96%	+35.98%	+35.92%
Oil and gas production:					
Remove grandfathering	+1.19%	+6.14%	+1.18%	+1.22%	+1.13%
Also remove anticipation	-14.65%	-18.42%	-14.64%	-14.71%	-14.51%
= Total change	-13.46%	-12.28%	-13.46%	-13.50%	-13.38%

Note: Each column re-solves the counterfactuals after halving or doubling a calibrated parameter — the permit cost c or the net drilling profit $\pi = q - c_{\text{drill}}$ — holding the estimated parameters fixed. Rows report the health-risk improvement (where an increase implies a reduction in health risk) and the change in oil and gas production from removing grandfathering, from also removing anticipation, and their total, each as a percent change from the implemented regulation, matching the decomposition in Table 6. Overall, the results are robust across all specifications.

Table A.3: Synthetic diff-in-diff robustness: donor pools

Specification	Anticipation (2018) $\hat{\tau}$ (%) [95% CI]	Regulation Period (2019) $\hat{\tau}$ (%) [95% CI]
Permits approved		
Benchmark (16)	+63.0 [+31.3, +81.6]	-19.0 [-52.4, +1.0]
Drop Oklahoma-dominated donors (11)	+63.3 [+31.0, +82.7]	-26.4 [-60.9, -5.8]
Drop gas-heavy donors (11)	+59.4 [+31.3, +87.4]	-28.0 [-58.1, +1.2]
Donor threshold 25 per quarter (14)	+62.9 [+31.6, +81.0]	-18.7 [-52.3, +1.7]
Wells drilled		
Benchmark (15)	-11.4 [-24.4, -0.8]	-19.0 [-37.0, -7.8]
Drop Oklahoma-dominated donors (10)	-15.0 [-33.6, -0.2]	-38.9 [-61.2, -24.4]
Drop gas-heavy donors (10)	-18.6 [-45.7, -1.2]	-32.2 [-67.9, -16.9]
Donor threshold 25 per quarter (13)	-15.7 [-34.3, -1.1]	-32.9 [-55.9, -17.9]

Note: Donor counts for each specification are in parentheses. Rows re-estimate the benchmark specification of Table 2 under alternative donor pools. The benchmark retains Oklahoma-dominated basins. 'Drop Oklahoma-dominated donors' removes basins with more than half of permit approvals in Oklahoma, where contemporaneous seismicity rules may have affected drilling; 'drop gas-heavy donors' removes basins with a pre-period oil share of production below 1/3; 'donor threshold 25 per quarter' raises the baseline requirement of an average of 10 approvals or spudded wells per quarter to 25. Confidence intervals are computed as in Table 2.

Table A.4: Counterfactual robustness to synthetic diff-in-diff donor pools

Specification	Health-risk improvement: Remove grandfathering	Also remove anticipation	Remove both
Benchmark	+28%	+8 pp	+36%
Drop Oklahoma-dominated donors	+39%	+5 pp	+44%
Drop gas-heavy donors	+39%	+4 pp	+43%
Donor threshold 25 per quarter	+33%	+5 pp	+38%

Note: Each row rebuilds the synthetic diff-in-diff moments, re-estimates the structural parameters, and simulates the counterfactual policies. The donor-pool definitions match those in Appendix Table A.3. The first column reports the percent reduction in health risk from removing grandfathering. The second reports the additional percentage point reduction from also removing anticipation, expressed relative to health risk under the implemented policy. The final column reports the total percent reduction from removing both features.

Table A.5: Pre-period covariate balance: Colorado vs synthetic Colorado

	Colorado	Synthetic Colorado	
		Permits ω	Drilling ω
Panel A: benchmark donor pool			
Mean $\log(1 + \text{oil bbl})$	10.28	9.24	8.41
Mean $\log(1 + \text{gas mcf})$	12.83	12.56	13.05
Mean lateral length (ft)	6,263	5,983	6,124
Panel B: drop gas-heavy donors			
Mean $\log(1 + \text{oil bbl})$	10.28	11.14	11.19
Mean $\log(1 + \text{gas mcf})$	12.83	11.94	12.26
Mean lateral length (ft)	6,263	6,091	6,338

Note: Table reports covariates for wells approved during the 2012Q1–2017Q4 pre-period. Synthetic Colorado is the ω-weighted donor-basin average, computed separately under the permit and drilling weights from the main synthetic diff-in-diff specifications. Panel A uses the benchmark donor pool; Panel B drops gas-heavy donor basins (pre-period oil share of production below 1/3), matching the corresponding row of Table A.3. Oil and gas are first-36-month cumulative production, with means computed over wells with recorded production; permits that were never drilled or have no reported production are excluded from these rows. In Panel A, the lower mean $\log(1+\text{oil})$ and higher gas levels for synthetic Colorado reflect gas-heavy donor basins whose wells produce little or no oil.

Table A.6: Robustness to hydrocarbon production transformations

	(1)	(2)	(3)	Spec. (3) implied %
log(1 + BOE), 1,000-barrel units				
Estimate	0.0940	0.0397	-0.0228	-2.2%
	(0.1067)	(0.1067)	(0.1059)	
log(1 + BOE), individual-barrel units				
Estimate	0.2077	0.1617	0.0093	+0.9%
	(0.2325)	(0.2337)	(0.2307)	
log(1 + value), dollars				
Estimate	0.2745	0.2336	0.0290	+2.9%
	(0.3094)	(0.3114)	(0.3070)	
log(1 + value), million dollars				
Estimate	0.0476	-0.0053	-0.0319	-3.1%
	(0.0594)	(0.0588)	(0.0587)	
Observations	1,308	1,308	1,308	
Basin and play fixed effects	No	Yes	Yes	
County fixed effects	No	No	Yes	

Note: Sample is Colorado wells spudded in 2019. Estimates are coefficients from the same within-Colorado permit-cohort regressions as Table 3. The baseline row measures BOE in 1,000-barrel units, matching Table 3; the individual-barrel row instead measures BOE in individual barrels. Value outcomes convert BOE to dollars using the same 65 dollars-per-BOE calibration as the production-value calibration in Section 5. The last column reports $\exp(\hat{\beta}) - 1$ for specification (3).

Table A.7: Texas placebo: permit cohort, location, and health exposure

	Colorado	Texas
Close to buildings (<1,500 ft)		
Estimate	-0.13	-0.0035
	(0.025)	(0.0061)
Percent change vs. mean	-34.21	-4.05
Hematological health-risk index		
Estimate	-0.11	-0.0062
	(0.027)	(0.0083)
Percent change vs. mean	-23.35	-4.81
Neurotoxicity health-risk index		
Estimate	-0.025	-0.0013
	(0.006)	(0.0018)
Percent change vs. mean	-23.68	-4.50
Hydrocarbon production, $\log(1 + \text{BOE})$		
Estimate	-0.023	0.061
	(0.11)	(0.043)
Implied percent change	-2.25	6.32
Observations	1,308	7,659
Basin and play fixed effects	Yes	Yes
County fixed effects	Yes	Yes

Note: Sample is wells spudded in 2019. The Colorado column repeats our preferred specification (which includes basin, play, and county fixed effects), column (3) of Table 3. The Texas column applies the same specification to Texas wells. Texas had no analogous setback rule, so the Texas column serves as a placebo test here.

Table A.8: Counterfactual effects by simulation horizon

	Remove grandfathering		Also remove anticipation		Total change	
Horizon	Health	Production	Health	Production	Health	Production
Through 2019Q4	+28%	+1%	+8%	-15%	+36%	-13%
Through 2020Q4	+22%	+1%	+4%	-10%	+26%	-10%

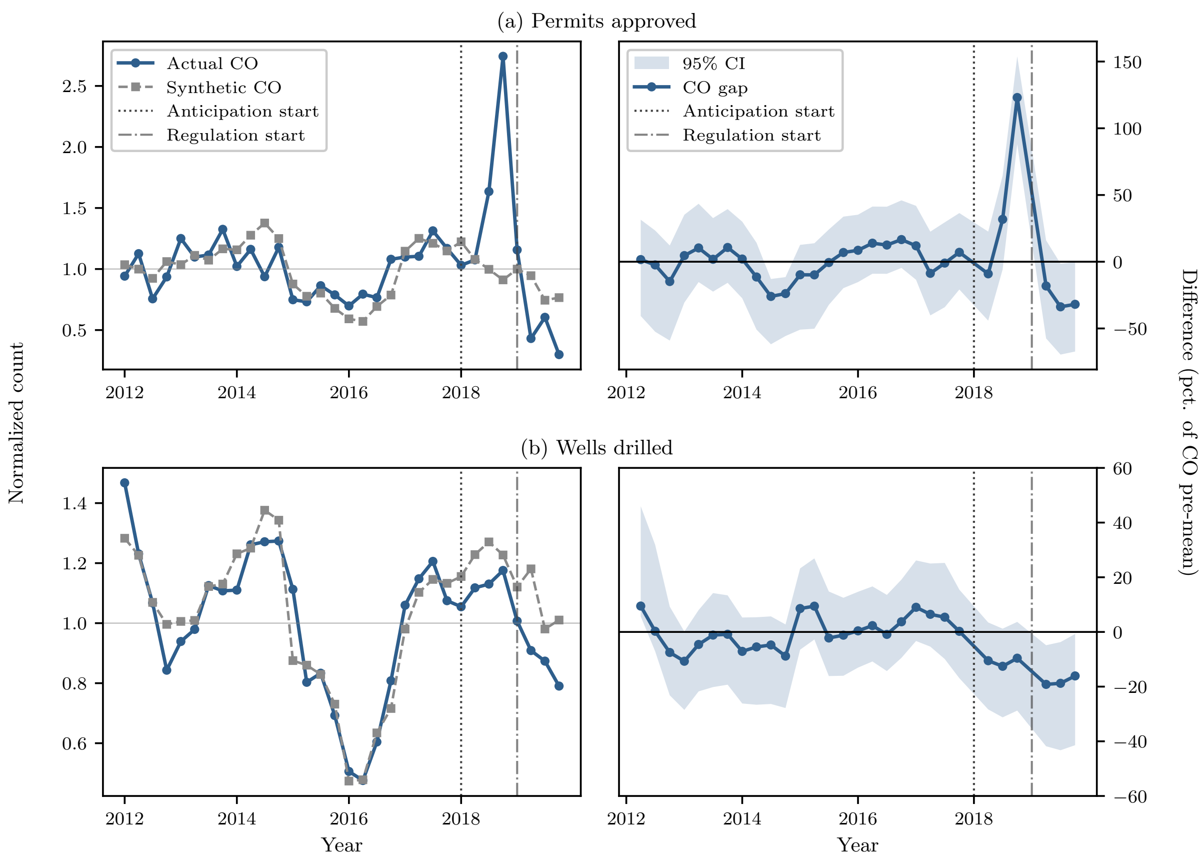
Note: Each row recomputes the policy effects of Table 6. The baseline is the 2019Q4 row.

D Additional Figures

D.1 Synthetic Diff-in-Diff Fit and Full-Sample Gaps

Figure A.4 shows the fit diagnostics behind Figure 2. Each row corresponds to one outcome. The left column plots Colorado and its synthetic counterfactual, normalized by each series' pre-period mean. The right column plots the two-quarter smoothed synthetic diff-in-diff gaps over the full 2012–2019 display window.

Figure A.4: Synthetic diff-in-diff fit and full-sample event-study gaps



Note: Left panels plot Colorado and synthetic series, normalized by each series' pre-period mean. Right panels plot two-quarter smoothed synthetic diff-in-diff gaps for Colorado relative to its synthetic counterfactual. We construct pointwise 95% confidence intervals using the conformal test-inversion procedure of Chernozhukov et al. [2021]. Vertical lines mark the start of anticipation (2018Q1) and regulation (2019Q1). Figure 2 reports the same gap estimates in the main text. Intervals are constructed pointwise at the 95% confidence level, so one or two intervals excluding zero among the 23 pre-anticipation estimates can arise by chance even when the underlying differences are zero.

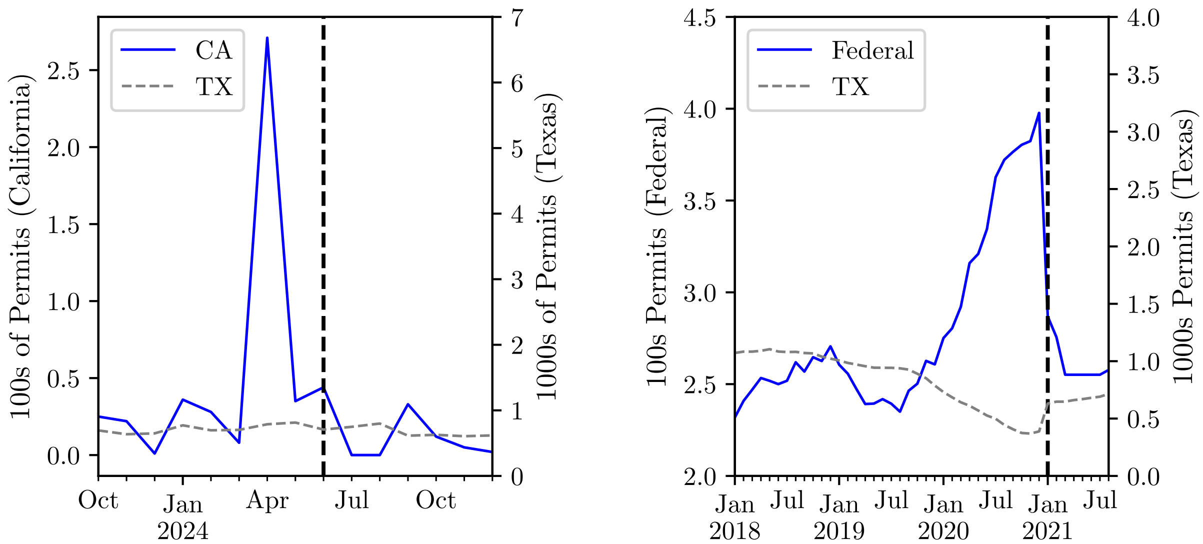
D.2 Other Markets: Permits Control Comparison

Figure A.5 reproduces the permit series from Figure 6, 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 A.5: Permits in other markets with Texas permits as control

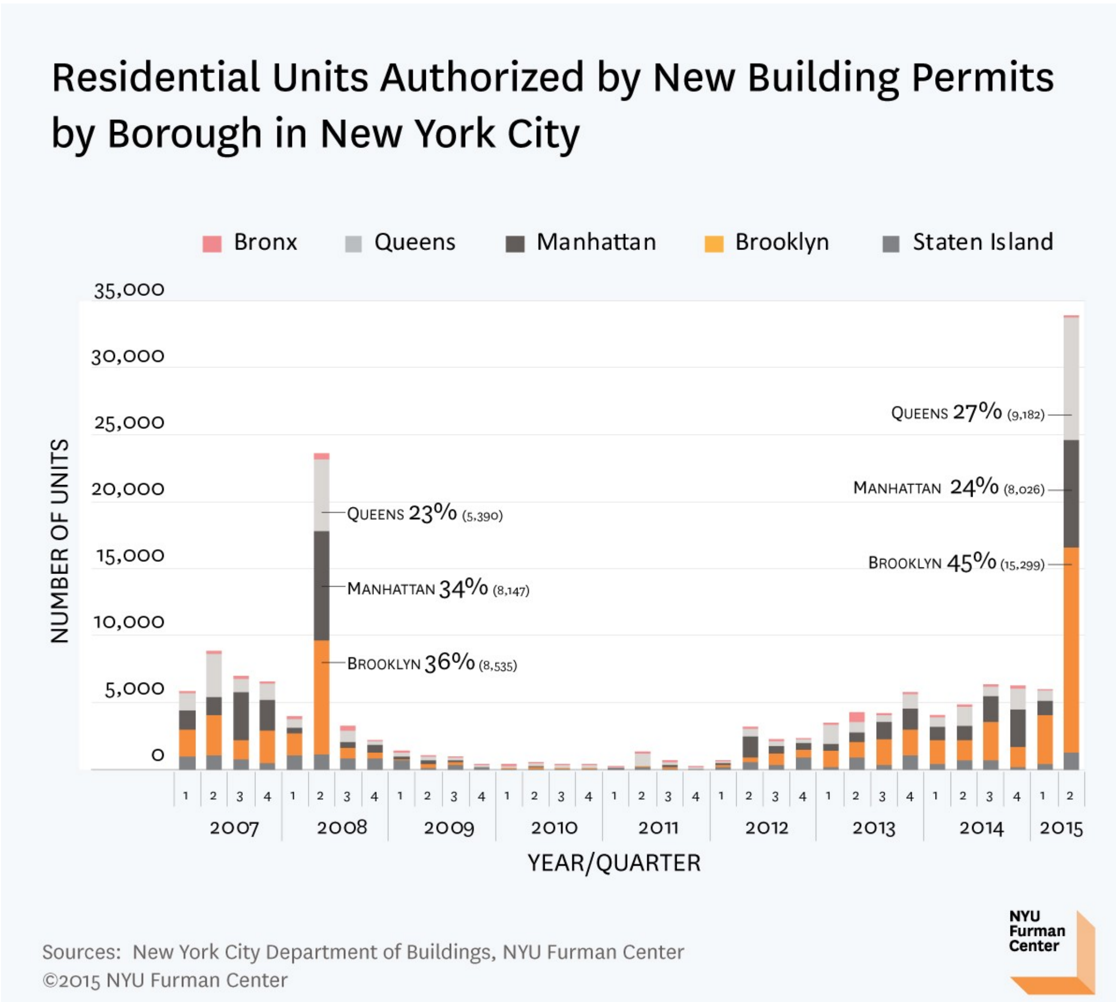
(a) California vs. Texas permits

(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 A.6: 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. The 2008 spike in permitting was also in response to an anticipated regulatory change. Source: NYC Department of Buildings, NYU Furman Center.