# The Surprising Static and Dynamic Effects of Oil and Gas Flaring on Agriculture*

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**Abstract**

Upstream energy producers frequently flare and vent excess gas. We demonstrate that flaring and venting cause surprising static physiological and dynamic economic spillovers for proximate agricultural operations. Using confidential crop insurance data from Alberta, Canada, we show that: i) flaring and venting affect current-period productivity of cropland and ii) farmers respond to static productivity shocks by changing investment decisions in subsequent periods. This unexpected dynamic response occurs because income tax rules alter farm investment incentives following a positive revenue surprise. Local projection models demonstrate how current-period environmental shocks influence future farm operations even after the contemporaneous effect abates.

## 1 Introduction

Environmental conditions shape contemporaneous outcomes. These same conditions may also influence intertemporal incentives, especially in the presence

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of government policy that distorts investment decisions. As a result, variation in static (i.e., contemporaneous) environmental effects may have dynamic (i.e., future) consequences, even after the environmental change abates. This is particularly relevant in agriculture, where environmental factors are a key determinant of productivity and producers are subject to myriad policies tied to investment such as taxes, subsidies, and standards. Yet, while a growing literature relates transitory environmental variables (e.g., temperature, precipitation, or air pollution) to agricultural activity (Schlenker and Roberts, 2009; Sanders and Barreca, 2022; Huang, Guo and Zhao, 2023), whether these factors further interact with policy to induce dynamic effects is less clear.

We study the connection between static physiological effects and dynamic economic incentives in a setting with rich farm-level data that relates to a pressing policy debate: the effects of oil and gas flaring and venting (i.e., burning or releasing gases) on agricultural producers. We first demonstrate that flaring and venting, sources of air pollutants such as sulphur dioxide and ground-level ozone, cause contemporaneous changes in the productivity of proximate agricultural operations. Then, through a policy interaction channel, we highlight how these static effects induce dynamic investment responses by affected farms.

Estimating the effects of flaring and venting, be they static or dynamic, has value in its own right. Flaring and venting are byproducts of crude oil and natural gas extraction, caused by either a lack of infrastructure or safety concerns (Alberta Energy Regulator, 2022). Both are common in upstream oil and gas development.[1] They emit greenhouse gases – thus contribute to climate change – and are important sources of local air pollution.[2] As such, there have been calls to heavily regulate these activities by both international organizations and governments (e.g., World Bank, 2022*b*). Yet, despite international pressure to limit flaring and venting, little is actually known about the economic consequences of such actions (Agerton, Gilbert and Upton Jr, 2023). We offer new results on the unintended consequences of flaring and venting regulation while contributing to the environmental economics literature connecting static environmental

[1]Approximately 144 billion $m^3$ of natural gas – or 15% of total annual US gas production – was flared globally in 2021 (World Bank, 2022*a*). Global estimates do not exist for venting.

[2]Flaring emits carbon dioxide, nitrogen oxides, volatile organic compounds (VOCs), and sulphur dioxide; venting emits methane, heavier hydrocarbons, nitrogen, VOCs, and hydrogen sulphide (Strosher, 2000; Johnson and Coderre, 2012).

effects to intertemporal economic behavior.

Our research design combines 18 years of confidential data on agricultural operations at the farm-field level from Alberta, Canada with spatially explicit environmental shocks linked to oil and gas development. We start by demonstrating that per-acre crop yields are affected by the pollution tied to flaring and venting activity. For the three major Albertan crops – barley, canola, and wheat – we find *increased* yields in response to flaring of between 0.3% to 0.7% per million cubic meter (mcm) of exposure, but *decreased* yields of between 0.1% to 0.5% per mcm of exposure to venting. The primary mechanism explaining the positive static yield responses is shown to be sulfur fertilization linked to the combustion of hydrogen sulfide from sour gas wells. While surprising, these results mirror those of Sanders and Barreca (2022) who examine the consequences of sulfur dioxide emissions from coal-fired electricity on crops in the United States.

Next, we demonstrate that farm operators make investments in response to flaring and venting exposure. To be clear, the static yield effect alone is not the cause of these dynamics. In fact, as our conceptual model demonstrates, there is no inherent reason why a static yield shock should induce a dynamic response. Rather, investment follows from an unintended policy interaction. The Canadian *Income Tax Act* contains a unique provision that allows for the complete write-off of investment in agricultural land. We find that flaring leads farms to cultivate an additional 7.6 acres of land per mcm of exposure in the year following exposure. This effect persists and represents a roughly 3% expansion within four years for the average farm. Negative shocks from venting, as predicted by our model, have no effect on farm expansion or contraction.

While important for understanding the consequences of changes in environmental conditions, our dynamic results are not unique to flaring and venting. As we show, any shock to farm incomes, such as a crop price spike, could trigger comparable dynamics. Still, a surprising unintended consequence of flaring and venting is that it does yield a dynamic investment response. There are both static and dynamic spillovers from oil and gas development to agriculture.[3]

[3]Moreover, from an empirical perspective, flaring and venting exposure is idiosyncratic and farm-specific, enabling us to leverage substantially more variation to uncover the tax-environmental policy interactions than could be exploited with regionally correlated price or weather shocks.

Rich data enable us to overcome many of the empirical challenges when estimating the static yield effects. Farm exposure to flaring and venting is plausibly exogenous, firm-specific, varies over time, depends on proximity to oil and gas activities, and, critically, is related to the sulfur content of specific wells. Flaring and venting is also unrelated to most macroeconomic conditions relevant to the agricultural industry. Investment, in contrast, is inherently dynamic. We investigate dynamics via impulse response functions of acres planted, estimated using local projections (Jordà, 2005). Local projections predict farms' investments over different time-horizons relative to the pollution shock that occurs in a base period. The empirical challenge in this exercise arises from the panel structure of our data. Our investment response equation includes both farm fixed effects and a lagged dependent variable, so Nickell-bias is a concern (Nickell, 1981). We deal with this by estimating a Blundell-Bond system-GMM (Blundell and Bond, 1998) variant of a local projection.[4]

Neglecting dynamic responses of environmental effects can lead to inaccurate assessment of new regulations or mischaracterization of firm behavior (Cullen and Mansur, 2017). This is especially true when firm investment exhibits persistence with effects that linger even after temporary shocks have abated (Hawkins-Pierot and Wagner, 2023). Easily interpreted short-run estimates may exhibit complicated long-run responses once adjustments are made for pre-existing programs. In fact, policies based on short-run results may be poorly matched to longer-term objectives. Indeed, under-estimating the long-run response might lead decision-makers – and hence policy-makers – to under-price environmental quality. Over-estimating the response may encourage excessive averting behavior, harming citizens' well-being.[5] Accounting for long-run investment responses are especially important when designing policy for climate change adaptation. For example, positive short-run agricultural gains may lead private agents to over-develop marginal lands even as yields are expected to decrease due to future extreme heat (Schlenker and Roberts, 2009).

The dynamics in our setting resemble Hawkins-Pierot and Wagner (2023)

[4]To the best of our knowledge, a Blundell-Bond variant on a local projection has not been employed elsewhere. However, the idea was raised in Jordà (2023).

[5]Averting behavior is when individuals purposely avoid activities during periods of high pollution or undertake defensive expenditures to protect against exposure (e.g., Mansfield, Johnson and Van Houtven, 2006; Zivin and Neidell, 2009).

and Huang, Guo and Zhao (2023). Hawkins-Pierot and Wagner study the intertemporal consequences of current period energy prices in manufacturing. Using U.S. Census Bureau data from 1976-2011, they estimate that, *conditional on current energy prices*, a 10% decrease in first-year energy prices increases ongoing facility-level energy intensity by 3%. Hawkins-Pierot and Wagner argue that lock-in is due to adjustment costs which limit firms' abilities to re-optimize following a change in market or environmental conditions. In contrast, we find that a dynamic effect attributable to a pre-existing tax policy rather than technological lock-in. Still, in both their setting and ours, the effects of short-run conditions persist into the future, highlighting that dynamic responses may be quite different from those predicted using a static model. Huang, Guo and Zhao (2023) examine dynamics using a sample of farms in China between 2003-2013. They show how transitory, prior period rainfall shocks increase inputs allocated to farming in the current period. Unlike our emphasis on policy interactions, however, they attribute dynamics to overoptimism and "irrationality."

Our results also contribute to two additional literatures. First, we add to the few papers evaluating the implications of flaring and venting. Evidence is thin on the effects of flaring – and especially venting – on non-climate economic outcomes (Agerton, Gilbert and Upton Jr, 2023).[6] Blundell and Kokoza (2022), for example, demonstrate that flaring increases respiratory-related hospital admissions and Cushing et al. (2020) show flaring is associated with greater risk of pre-term births. By using detailed facility-level data on flaring and venting, we extend this literature to show production externalities can spill across economic sectors, leading to complex interactions that may be difficult to predict. This paper is also among the first to demonstrate the economic consequences of venting, as detailed venting data are rarely available.

Next, recent studies on air pollution and crop yields have offered conflicting results because of different pollutants; we provide new evidence. Metaxoglou and Smith (2020) and Sanders and Barreca (2022), respectively, examine the effect of reduced nitrogen oxide and sulfur dioxide emissions from coal-fired electricity generation on corn and soy yields in the U.S. They have opposing

[6]From a regulatory perspective, Marks (2022) estimates that a modest tax on methane emissions from natural gas production would yield climate benefits on the order of $1.8B. Lade and Rudik (2020) evaluate flaring regulations in North Dakota, finding that a uniform tax on flared gases would have meaningfully reduced the economic costs of the firm-specific rules.

conclusions. Metaxoglou and Smith (2020) demonstrate that nitrogen oxide emissions reduce yields, whereas Sanders and Barreca (2022) show that sulfur dioxide emissions improved yields.[7] Our results demonstrate both positive and negative effects of pollution on yields. In particular, our short-run flaring estimates support those of Sanders and Barreca (2022), where sulfur deposition improves agricultural productivity.

The remainder of this paper is organized as follows. Section 2 provides some institutional and regulatory background, introduces our data, and provides some descriptive statistics. Section 3 contains our analysis of the short-run effects of flaring and venting on agricultural yields. We explore the long-run effects of flaring and venting on investment in Section 4. Section 5 concludes.

# 2 Data and Institutional Background

## 2.1 Flaring and Venting: Background, Regulation, Data

Flaring and venting involve the release of gases into the atmosphere from oil and gas operations. Venting is when these gases are directly released. Flaring is when they are first burned in a flare stack. Both are frequently used to address associated gases found "in solution" in oil wells, which must be captured or released to process the oil. However, flaring and venting can also occur elsewhere in the upstream oil and gas industry, including at gas wells, gas processing plants, and pipelines. Our analysis includes releases from all sources.

Flaring and venting generate greenhouse gases (GHGs). Venting involves the direct release of methane, a potent GHG, while flaring converts methane into carbon dioxide. Flaring and venting also generate a range of local air pollutants. Pollutants from flaring and venting reflect the composition of the solution gas. Composition, and thus emissions, vary substantially across reservoirs.

[7]Using satellite data, a handful of other studies demonstrate a negative relationship between ambient air pollution and crops yields. For example, Lobell, Di Tommaso and Burney (2022) show a negative association between nitrogen oxide concentrations and crop greenness across China, India, Western Europe, and North and South America, Liu and Desai (2021) provide evidence that aerosols and ozone reduce maize and soybean yields in the U.S. (with negative interaction effects with heat), McGrath et al. (2015) and Lobell and Burney (2021) find air pollution in the US decreases maize and soybean yields for 1999 to 2018 and Hong et al. (2020) find ozone concentrations and yields are negatively correlated for perennial crops in California.

Methane is the most prevalent pollutant associated with venting, but other heavier hydrocarbons, such as ethane and propane, in addition to nitrogen, hydrogen sulfide, and carbon dioxide are common (Johnson, Kostiuk and Spangelo, 2001; Johnson and Coderre, 2012). Methane, nitrogen oxides, and volatile organic compounds are important precursors to ground-level ozone (West et al., 2006), which is known to be detrimental to crop health (Emberson, 2020).

Flaring induces a range of chemical reactions yielding a different mix of pollutants.[8] Importantly, when associated gases contain hydrogen sulfide, it is referred to as 'sour gas'. Flaring sour gas produces sulfur dioxide. Alberta has a high prevalence of sour gas wells combined with regulations that require gas with high hydrogen sulfide content to be conserved or flared. Sulfur dioxide is the primary concern for flaring's potential impact on crop yields. Notably, previous research established a positive relationship between sulfur dioxide and agricultural yields (Sanders and Barreca, 2022),

Oil and gas operators in Alberta are subject to a range of restrictions on flaring and venting activities. (Appendix A provides an overview of the province's regulatory landscape.) All licensed oil and gas operators must publicly report volumes of gas flared and vented at each site on a monthly basis (Alberta Energy Regulator, 2021). These data cover more than 98% of all flaring and venting in the province.[9] Our analysis uses data for 2002 to 2019, encompassing 42,184 unique facility IDs, composed of 464,613 flaring records across 21,593 unique facilities and 1,019,817 venting records across 31,276 unique facilities.

Figure 1 illustrates the province-level time series variation of facility counts, and venting and flaring volumes in our data. Appendix B contains comparable time series plots with the data disaggregated into seven smaller Census Agricultural Regions. Panel A of Figure 1 shows the number of facilities reporting information to the regulator. An upward trend is apparent from 2010 through 2015. This trend tracks the expansion of the Alberta oilsands, in particular the growth of steam-assisted gravity drainage, or SAGD technology.[10] Panel B shows substantial volatility in flaring and venting volumes but that

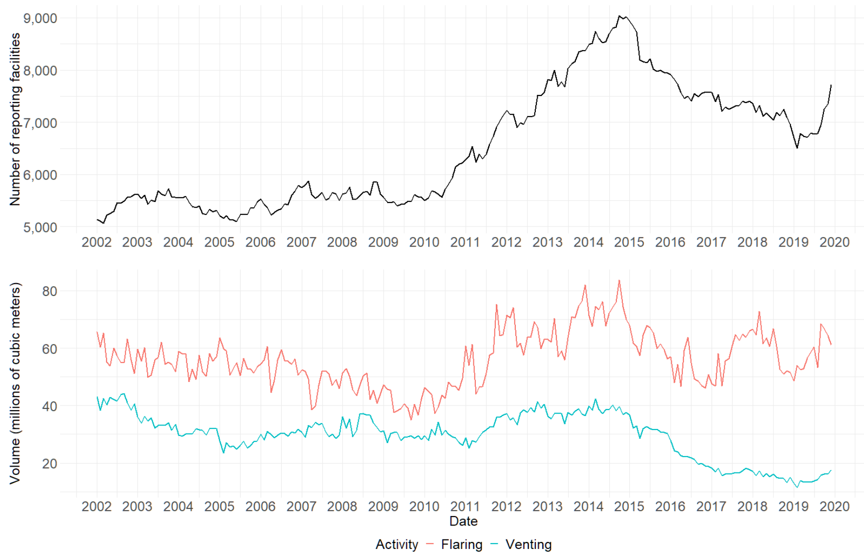
[8] These include carbon dioxide, volatile organic compounds, nitrogen oxides, particulate matter and a range of carcinogenic compounds (Strosher, 2000). Emissions also vary with flare efficiency, which depends on technical and environmental factors (Caulton et al., 2014).

[9] Only flaring and venting activity from confidential facilities are excluded.

[10] SAGD represents a method to extract bitumen without developing large surface mines.

aggregate volumes remained relatively constant even as production increased. Stated differently, flaring and venting intensities have fallen in the Alberta oil-patch. (Appendix Figure B.1 also shows notable regional differences, with some regions seeing increased emissions, while others with marked declines.)

Figure 1: Trend in Flaring and Venting Activity in Alberta, 2002-2019




Facilities report flaring and venting data monthly. They are identified in space via a legal subdivision (LSD), which is a 400m x 400m grid tile contained in the Alberta Township System (ATS). Each LSD is defined by a centroid using ATS shapefiles. We aggregate flaring and venting activity to the LSD-month level, resulting in 1,379,983 observations over the period 2002-2019.

## 2.2 Agricultural Yield and Acreage Data

Confidential data on farm-specific agricultural yields were provided by the provincially owned Agriculture Financial Services Corporation (AFSC). AFSC is the main provider of crop insurance and financial services to farmers in Alberta.

AFSC crop insurance contracts require farmers to report annual yield and acres planted data at the field level. These yields and acreage decisions are our main variables of interest. The data include observations for 33 commodities over our period of analysis. We focus on wheat, barley and canola as these are the key cash crops in the province, representing 84.1% of total acreage in

Alberta.[11] Each field in the data is associated with a set of coordinates that represent the field centroid. However, claiming the data are field-level is not fully accurate: conversations with AFSC staff emphasized that many farmers report farm-by-commodity yields rather than field-by-commodity yields. We thus work with the slightly coarser annual farm-by-commodity data. The resulting farm-level dataset contains 394,950 observations over 2002 to 2019.

Figure 2 shows the spatial distribution of farming, flaring, and venting activity in Alberta for 2002 and 2019.[12] Each point represents a farm or facility. Black dots are for farms. Red dots are for flare stacks. Blue dots are venting sites. The size of the "dot" reflects the size of the farm or the volume of gas flared or vented. Fossil fuel activity is clearly distributed according to the underlying resource; yet, also apparent is the variation in the type and location of the activity over time. We leverage both the time series and spatial variation to pin down the effects of flaring and venting on agricultural production.

In addition to yield data, we also obtain field-level acreage data from AFSC. As acreage is the variable upon which AFSC insures production, the agency expresses high confidence in the accuracy of acres planted at the farm-level.

### Weather Data

All models in this paper, both static and dynamic, contain extensive weather covariates. Weather is the critical time-varying input into agricultural output.[13] In particular, Schlenker and Roberts (2009) demonstrated a strong non-linear relationships between weather, especially heat, and crop yields (also see, Robertson et al., 2013). As such, we control for time-varying weather by estimating the Schlenker and Roberts (2009) production function.

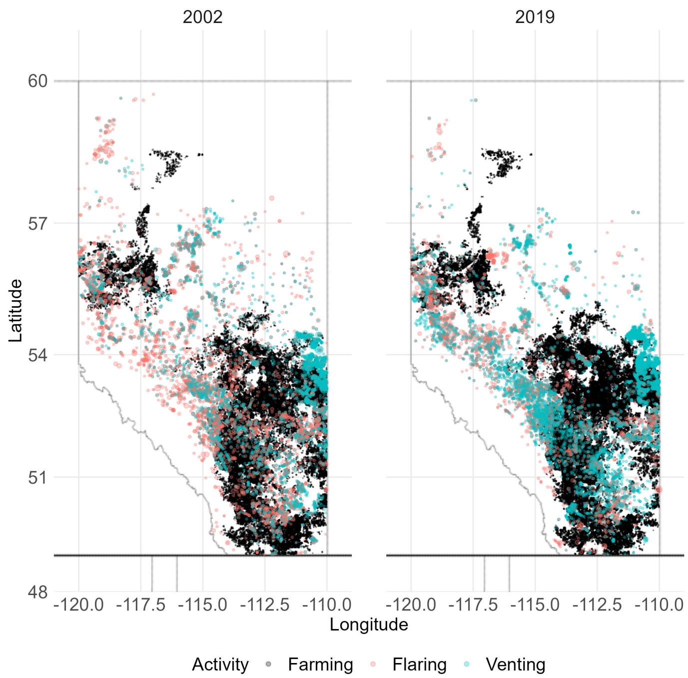
Historical weather data were obtained from the Government of Alberta Agro-Climatic Information Service. These data include daily minimum and maximum temperatures, daily precipitation (mm), and relative humidity. As our

[11] Alberta accounts for 31.4% of Canada's total wheat production, 36.7% of canola and 47.7% of barley (Statistics Canada, 2023). The AFSC data covers approximately 75% of acres planted in Alberta for each of these crops.

[12] Additional supporting figures are available in the Online Appendix. Figure B.3 shows additional detail on the co-location of farms and flaring/venting sites. Figure B.2 shows the spatial distribution of exposure in annual volumes of flaring and venting across townships. Figure B.4 shows how acreage planted by crop is distributed across the province.

[13] Moreover, unlike input prices for fertilizer, weather varies cross-sectionally within years.

Figure 2: Farming, Flaring, and Venting Activity in Alberta, 2002 and 2019




data are limited to daily minimum and maximum temperatures, we interpolate hourly temperatures following Cesaraccio et al. (2001). Cesaraccio et al. (2001) estimate hourly temperatures from daily maximum and minimum temperatures and sunrise and sunset times using a piecewise function consisting of two sine functions and a square root function. Daily sunrise and sunset times were mapped to the township level using the latitude and longitude associated with the centroid of each township. All weather information was mapped to the field-level agricultural yield data by township ID.

## 2.3 Summary Statistics

To review, we link flaring and venting volumes and weather data to the field centroids.[14] Flaring, venting, yields, and acreage vary spatially in the cross-section

[14]We map each flaring and venting site, denoted by an LSD coordinate, to fields using fixed radii distances. Our preferred results start with a 50km, consistent with the specifications in Metaxoglou and Smith (2020) and Blundell and Kokoza (2022), then we exclude a 5km hole immediately around the fields. We retain only flaring and venting volumes emitted within a growing season, defined as April to August (Robertson et al., 2013). Figure B.5 in Appendix

and intertemporally within space. Because of the nature of yield reporting, we aggregate flaring and venting exposure to the farm level by performing an acreage-weighted average across all fields. We also trim the top and bottom 1% of the sample for yield by crop to account for potential misreporting of yields. After aggregating and trimming, we obtain 138,982 farm-by-year observations for wheat, 130,421 observations for canola and 117,193 observations for barley. Summary statistics for the key variables are presented in Table 1.

Table 1: Summary Statistics

| | Barley | | Canola | | Wheat | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Acreage per Farm | 358.4 | 660.0 | 542.9 | 798.3 | 620.9 | 904.6 |
| Yield (kg/acre) | 1,321.8 | 563.6 | 814.4 | 298.1 | 1,282.5 | 525.4 |
| Flaring (mcm in 50km) | 4.1 | 3.6 | 3.7 | 4.0 | 3.8 | 3.9 |
| Venting (mcm in 50km) | 3.8 | 11.3 | 3.9 | 11.0 | 3.3 | 10.2 |
| Precipitation (mm) | 403.8 | 89.7 | 397.5 | 82.0 | 387.7 | 85.4 |
| Humidity (g/m$^3$) | 65.2 | 4.1 | 65.6 | 3.9 | 64.7 | 4.2 |
| Temp. 0-9°C (hrs) | 910.8 | 128.1 | 894.7 | 120.7 | 875.8 | 121.4 |
| Temp. 10-19°C (hrs) | 1,613.5 | 124.0 | 1,642.4 | 116.4 | 1,621.7 | 119.5 |
| Temp. 20-29°C (hrs) | 653.9 | 126.5 | 653.0 | 122.9 | 682.7 | 129.2 |
| Temp. 30-40°C (hrs) | 27.5 | 34.8 | 21.2 | 28.7 | 33.5 | 41.5 |
| Observations | 117,193 | | 130,421 | | 138,982 | |

This table presents summary statistics for variables used in the subsequent analysis. Flaring and venting data are publicly available and accessible from the Alberta Energy Regulator. Crop and agricultural data were confidentially provided by the Alberta Financial Services Corporation, the province's crop insurance provider.

On average, farms in Alberta plant 621 acres with wheat, 543 acres with canola and 358 acres with barley. The large standard deviations associated with these values reflect the wide range in farm sizes in the province. Less variation is apparent in yields per acre. The yield for barley, canola and wheat correspond to 1,322 kg per acre, 814 kg per acre and 1,283 kg per acre.[15] Flaring and venting are measured in million cubic metres (mcm). Farms experi-

B shows farm exposure at 1, 5, 10, 20, 30, 40 and 50km radii, with the expected increase in exposure as surface area increases.

[15]We maintain AFSC's unit of measure for yields, using kilograms per acre rather than the more familiar bushel. As an example, there are approximately 27.2 kg per bushel of wheat, so average yield for wheat is roughly 47.2 bu per acre.

ence average annual flaring exposure of between 3.7 mcm and 4.1 mcm, with meaningful variation over time and across space. Likewise, venting exposure averages range from 3.3 mcm to 3.9 mcm.

# 3 The Static Yield Response to Flaring and Venting

## 3.1 Set-up and Econometric Specification

There is a compelling basis to suspect that flaring and venting might impact agriculture. Pollutants associated with flaring and venting have been shown to be toxic to plants (Kulshrestha and Saxena, 2016). Emissions from flaring and especially venting, such as methane, VOCs and nitrogen oxides, contribute to the formation of ground-level ozone and ozone is harmful to crops (Emberson, 2020; Avnery et al., 2011).[16] The relationship is not uniformly negative, however. The crop-response to prominent pollutants, such as sulfur dioxide, are non-linear. Higher concentrations decrease photosynthesis and damage plant leaves. Lower concentrations have been shown to increase photosynthesis and improve plant growth (Ausma and De Kok, 2019). Sulfur dioxide is a product of sour gas flares. Thus, the level and mix of exposure determines the relationship.

We explore the physiological relationship between flaring and venting and agriculture by regressing farm-by-crop yields on exposure volumes. For each major crop – wheat, canola and barley – we specify:[17]

$$\ln(\text{Yield}_{it}) = \beta_1 \text{Flare}_{it}^{50km} + \beta_2 \text{Vent}_{it}^{50km} + \boldsymbol{W'_{it}\theta} + \rho_i + \gamma_t + \varepsilon_{it}. \tag{1}$$

The dependent variable is $ln(\text{Yield}_{it})$, the log of per acre output from farm $i$ in

[16]Flares also emit heat and light. Compared with pollution, we view heat and light as an unlikely physiological mechanism for two reasons. Alberta regulations limit the total radiant heat received at ground level from flares (Alberta Energy Regulator, 2022) and specify setback and stack height requirements for flare stacks in the *Oil and Gas Conservation Rules*, *Directive 060*, the *Forest and Prairie Protection Regulation*, and *Directive 056*. Further, our "donut" specifications omit flaring and venting volumes around the immediate vicinity of the fields, where potential heat and light effects are more likely.

[17]Models are estimated separately for each crop as the physiological relationship between pollution and output may differ across crops.

year $t$. We estimate models using a 50km-5km donut distance specification. To implement the "donut specification", we start by including all farms in our data. For each farm we map flaring and venting volumes within a 50km radius of the farm (other radii are included in the Appendix as robustness). Next, we remove any flaring and venting activity that occurs within a 5km radius of the farm. We are left with a series of "donuts" that have an outer radius of 50km with a series of 5km holes around farm locations. Our flaring and venting variables are thus purged of any exposure within a 5km radius of the farm.

There is clear motivation for a donut specification. Drilling and operating oil wells disturbs the physical region around the site. This happens both in the process of setting-up a rig, by moving equipment to and from drill sites, and through conducting maintenance. These operations may directly affect yields because agricultural land may be appropriated for oil development, or indirectly as emissions from diesel vehicles may contribute to the local pollution. As we are interested in pinning down the effect of flaring and venting emissions, we want to minimize spillover pollution from these associated activities.[18]

Our parameters of interest are $\beta_1$ and $\beta_2$. $\beta_1$ captures the approximate percentage change in yields due to an additional mcm of growing season flaring volumes emitted with 50km of farm $i$ in year $t$. $\beta_2$ measures the corresponding effect for venting releases. Unlike Metaxoglou and Smith (2020) and Sanders and Barreca (2022), we do not measure air pollutants directly. We capture volumes flared and vented. As such, the estimands, $\beta_1$ and $\beta_2$, should be interpreted as reduced-form, intent-to-treat estimates. Our data allow us to exploit farm-level variation. Unfortunately, pollution monitors are sparse in rural and agricultural areas of Alberta and direct measures of ambient pollution concentrations are unavailable. However, in Section 3.4 we explore the effects of one pollutant, sulphur, using data on well hydrogen sulphide concentrations.

Our preferred models follow Metaxoglou and Smith (2020) in that we treat all flaring and venting volumes within a radius as equivalent (i.e., we do not reweight according to wind direction). A flexible set of weather controls are included via $\boldsymbol{W}_{it}$. We apply the Schlenker and Roberts (2009) production function by including 1°C temperature bins and cumulative precipitation controls. The temperature controls account for the effect of cumulative exposure and allow

[18] If any of these factors remain, we estimate the joint effect of flaring and venting plus drilling.

for nonlinear responses to heat. Schlenker and Roberts (2009) demonstrated that exposure to extreme heat causes rapid non-linear decreases in yields, so we calculate the number of hours spent within degree buckets, ranging from 0°C to 40°C, over the growing season. We also control for cumulative monthly precipitation and polynomials in humidity.

Next, (1) contains farm and year fixed effects, $\rho_i$ and $\gamma_t$. Our identifying source of variation is within farm across time exposure to flaring and venting emissions. Farm fixed effects absorb differences in the cross-section and control for slow moving stocks and farm invariant factors such as soil quality, irrigation status, and exposure to sunlight, among other factors. Time fixed effects capture time-varying factors common across farms in Alberta; for example, prevailing output and input prices, like energy and fertilizer, in addition to provincial policies. Taken together the total variation in farm yields explained by weather and fixed effects is 62%, 61% and 71% for barley, canola and wheat, respectively.

Finally, $\varepsilon_{it}$ is the error. Standard errors are clustered by farm to account for potential autocorrelation.

## 3.2 Evidence Supporting the Research Design

Alberta closely monitors and regulates flaring and venting. Clear rules on sulphur content, safety, the costs of capturing and transporting associated gases, and even acceptable returns on capital needed for infrastructure characterize when a facility is permitted to flare or vent. Combining this regulatory environment with geographical variation in production and infrastructure, temporal variation in oil and gas prices, plus set-backs and the donut specification supports the assumption that farm decision-making (and subsequent productivity) is independent of flaring and venting volumes. Still, we start our analysis by presenting evidence that bolsters this assumption. (Further, robustness and placebo checks are contained in Appendix D.)

The main concern with (1) is that, even after conditioning on fixed effects and controls, a potential omitted variable may be simultaneously correlated with the residual variation in crop yields and either flaring or venting. The richness of our data along with our empirical specification limits the channels in which this might occur. Nonetheless, we offer corroborating evidence that suggests bias due to omitted variables is unlikely.

We validate our research design by compiling information on agricultural land prices and testing whether variation in land prices are correlated with changes in flaring or venting exposure. The idea behind this test is as follows. Long-run agricultural productivity is capitalized into land prices. Inherently more productive acres obtain higher prices when transacted at arm's-length. Thus, finding a relationship between flaring and venting, phenomena which are temporary, and land prices, would suggest a potential issue with our design.

Municipality-level data from the Agricultural Real Estate Transfers database maintained by the Alberta government were collected (Alberta, 2022). Land prices are measured as the average per-acre market value of all agricultural transfers that occur within a municipality in a given year. There are 68 municipalities with agricultural land in Alberta. We also compile municipality-level analogues to all control variables in Equation (1).

To test for a relationship between agicultural land prices and flaring and venting, we run the following regression:

$$\ln(\textbf{Land Price}_{mt}) = b_1\textbf{Flare}^{50km}_{mt} + b_2\textbf{Vent}^{50km}_{mt} + \boldsymbol{W'_{mt}}\boldsymbol{\vartheta} + \tilde{\rho}_m + \gamma_t + u_{mt}, \qquad (2)$$

where $\ln(\textbf{Land Price}_{mt})$ is the natural log of land prices, $\textbf{Flare}^{50km}_{mt}$ and $\textbf{Vent}^{50km}_{mt}$ are the flaring and venting levels that occur within 50 km of a municipality, and $\boldsymbol{W_{mt}}$ are municipal weather controls analogous to those in (1). $\tilde{\rho}_m$ and $\gamma_t$ are municipality and year fixed effects, $u_{mt}$ is an idiosyncratic error. Standard errors are clustered by municipality.

The estimands from this regression, $b_1$ and $b_2$, give the semi-elasticity of land prices with respect to changes, respectively, in municipal flaring and venting exposure. Results are presented in Appendix D (including specifications that omit controls and fixed effects). Across specifications virtually no relationship between flaring and venting and land values is observed. Coefficients $b_1$ and $b_2$ are both statistically and economically insignificant with a 95% confidence interval ranging from -0.0005 to 0.0032 for $b_1$ and from -0.0021 to 0.0021 for $b_2$. Using the upper bounds of these intervals, a 100% increase in flaring exposure would cause, at most, a 3% increase in land prices, while a doubling in venting would cause a 1% increase in prices.[19] The effects on the down-side are even smaller. Flaring and venting have minimal bearing on contemporaneous municipal agricultural land prices, a necessary (but not sufficient) condition for the validity of our research design.[20]

## 3.3 Effect of Flaring and Venting on Agricultural Yields

The effect of flaring and venting on agricultural yields is shown in Table 2. Three models are presented, one for each of barley, canola and wheat. The coefficients reflect the percent change in yields per acre for a one mcm increase in emissions. Each is a donut specification that contains farm and year fixed effects as well as a flexible complement of weather controls.

The pattern across commodities is consistent. For barley, there is a 0.7% increase in yield for every mcm increase in contemporaneous flaring volumes. Average flaring per 50km radius equals slightly more than 4 mcm with notable intertemporal variation in exposure. Canola and wheat yields, likewise, increase in response to flaring exposure. Canola yields increase by 0.3% per mcm of flaring, while wheat yields increase by 0.6%.

Most wells in Alberta are sour gas wells, with associated gases containing hydrogen sulphide. Regulations in Alberta require high sulphur gas to be flared (Alberta Energy Regulator, 2022). Combustion of hydrogen sulfide through flaring creates sulfur dioxide, increasing the amount of sulfur available for crops. These estimates therefore mirror the fertilization findings of Sanders and Barreca (2022). By studying the unintended consequences of the US Acid Rain Program, Sanders and Barreca (2022) find that ambient sulfur pollution increases agricultural yields. Both Sanders and Barreca (2022) and our estimates show that industrial pollution spillovers can prompt unexpected outcomes. Regulation aimed at reducing acid rain and climate change may bring about negative short-run consequences for agriculture.

In contrast to flaring, venting decreases agricultural yields. An increase of

[19] Average municipality-level flaring is 9.8 mcm and venting is 5.2 mcm.

[20] Note that even if flaring and venting directly affect agricultural productivity, there would still be limited scope for a contemporaneous relationship between exposure and land prices. As yields are observed at the end of a growing season, land-market participants would only observe changes in land productivity after the growing season (typically September or October).

one mcm in venting volumes causes yields of barley, canola, and wheat to fall by 0.5%, 0.1%, and 0.3%, respectively. Each of these effects is precisely estimated. Venting is primarily methane, which contributes to ozone formation that reduces plant yields. Our venting results mirror the findings of Metaxoglou and Smith (2020), who find that nitrogen oxide emissions – which also contribute to ozone formation – from coal fired power plants decreased crop yields.

Table 2: Effect of Flaring and Venting on Yields

| | Barley | Canola | Wheat |
|---|---|---|---|
| Flaring volume (mcm) | 0.007 | 0.003 | 0.006 |
| | (0.001) | (0.001) | (0.001) |
| Venting volume (mcm) | -0.005 | -0.001 | -0.003 |
| | (0.001) | (0.000) | (0.000) |
| No. of farms | | | |
| Obs. | 117,193 | 130,421 | 138,982 |

All models contain: (1) flexible weather controls including the number of growing season hours within 1°C temperature bins, cumulative precipitation and polynomials in humidity; (2) farm-specific fixed effects and (3) year fixed effects. Standard errors are clustered on individual farms. The dependent variable is logged kg per acre and exposure variables are measured as volumes emitted within 50km of a farm dropping emissions that occur within 5km of the farm.

We explore the robusness of these results in Appendix D. Estimates are unchanged if we forego the donut specification that removes exposures within 5km of farms. The flaring results are robust to varying distances of exposures from 5km to 50km, with larger coefficients and standard errors at shorter distances. Venting results are not significant at exposure distances less than 10km, but consistent and significant for barley and wheat from 50km to 20km. Venting results for canola are consistent but not significant until distances of 40km and 50km. Finally, the results are largely unaffected by controlling for oil and gas production from crude oil and bitumen batteries within 50km of farms.

## 3.4 Exploring the Sulphur Deposition Mechanism

Flaring and venting release different pollutants. The preceding results compared our results to Sanders and Barreca (2022), arguing that sulphur deposition is the mechanism behind the yield response to flaring. While precise emission mixes from vents and flare stacks are unknown, it is possible to indirectly test for the role of sulphur deposition.

Provincial rules treat high sulphur-content wells differently than low sulphur wells. High sulphur wells are thus classified with sour gas licenses. To test the sulphur deposition mechanism, we identified all sour wells following the procedure outlined in Online Appendix C. Most wells in Alberta contain some sulphur even if there are not formally classified as sour wells. Sulphur content is, therefore, a matter of degree. We refer to all non-sour licenses as sweet wells, but stress that these "sweet wells" likely contain some sulphur.

To examine the sulphur deposition mechanism, we re-estimated (1) including flaring and venting of sour gas and sweet gas as separate variables. Estimates are shown in Table 3. For each of barley, canola and wheat, coefficients are shown for sweet and sour flaring plus sweet and sour venting.[21] Estimates for barley are especially striking. The positive effect of flaring on yields is entirely driven by flaring from sour gas wells: Yields increase by 1.3% per mcm of exposure to sour flaring, with no corresponding effect from sweet flaring. For venting, exposure to sour gas actually *increases* yields by 0.7% per mcm, but exposure to sweet gas decreases yields by 0.6% per mcm. Wheat shows a similar, though moderately less striking, pattern. Sour gas flaring increases yields more than sweet flaring, with estimates of, respectively, 0.7% and 0.4% per mcm. Further, sour gas venting *increases* yields by 0.9% per mcm, while sweet venting has a negative effect on yields equal to a 0.5% decrease per mcm. Overall, as in Sanders and Barreca (2022), these results for barley and wheat offer compelling evidence that sulphur deposition is the mechanism linking flaring to agricultural yields.

Table 3 also contains results for canola. At first pass, estimates for canola appear to undermine the sulfur fertilization channel. Sour and sweet flaring values are both positive, while the effects of sour venting are negative. However, these results are explained by the widely-understood (to farmers) agronomy of canola. Canola is known to demand large volumes of sulfur fertilizer and is particularly sensitive to sulfur deficiency. Moreover, application of additional

[21] Regulations require routine releases of sour gas to be flared, btu venting still occurs at sour gas wells if required for safety or operational purposes.

Table 3: Comparing Sour and Sweet Flaring and Venting

| | Barley | Canola | Wheat |
|---|---|---|---|
| Sour flaring (mcm) | 0.013 | 0.002 | 0.007 |
| | (0.002) | (0.001) | (0.001) |
| Sour venting (mcm) | 0.007 | -0.003 | 0.009 |
| | (0.002) | (0.001) | (0.001) |
| | | | |
| Sweet flaring (mcm) | 0.000 | 0.004 | 0.004 |
| | (0.001) | (0.001) | (0.001) |
| Sweet venting (mcm) | -0.006 | -0.001 | -0.005 |
| | (0.001) | (0.000) | (0.000) |
| No. of farms | | | |
| Obs. | 117,193 | 130,421 | 138,982 |

All models contain: (1) flexible weather controls including the number of growing season hours within 1°C temperature bins, cumulative precipitation and polynomials in humidity; (2) farm-specific fixed effects and (3) year fixed effects. Standard errors are clustered on individual farms. The dependent variable is logged kg per acre and exposure variables are measured as volumes emitted from either a sour or sweet well within 50km of a farm dropping emissions that occur within 5km of the farm.

sulfur beyond that factored into standard farming practice does little to further increase yields (Karamanos, Goh and Flaten, 2007). Therefore, because farmers actively manage sulfur for canola by regularly testing and fertilizing soil, we would not expect, and do not find, additional sulfur fertilization from industrial pollution to influence yields. Instead, the canola results in Table 3 suggest that sulfur fertilization is not a relevant margin for canola. Rather, it may be an alternative fertilization effect associated with flaring (such as a low dose of nitrogen) that influences canola yields. Further exploration of other pollutant-specific mechanisms is left to future work.

The main conclusion from the short-run analysis is that flaring, surprisingly, causes agricultural yields to increase, while venting causes them to decrease. The next step demonstrates how this static physiological result induces a dynamic economic phenomenon through interactions with government policy.

# 4 The Dynamic Investment Response to Flaring and Venting

Sulphur deposition is a short lived (i.e., static) phenomenon as soils are prone to leaching in dormant winter months (Alberta, 2024*b*).[22] Yet, as we next demonstrate, the static physiological spillover from oil and gas development to agriculture also induces a dynamic response. Specifically, farmer decision-making interacts with tax policy to convert the static biological relationship into a dynamic economic effect. This surprising dynamic response to flaring and venting arises because modest reductions in the after-tax cost of new land provides strong incentives for farm investment even if this investment moves the farmer away from the optimal farm size (House and Shapiro, 2008).

A conceptual framework of agricultural investment shows the static-dynamic relationship clearly. It highlights the tax policy channels through which exposure to flaring or venting change a farm's incentive to invest in land. Connecting static environmental effects to dynamic economic incentives adds new dimensions to our understanding of economically meaningful consequences of pollution.[23] The conceptual framework then guides our empirical analysis. We use local projections to estimate an impulse response function for farm investment, flexibly capturing the time series features of our setting, and testing the predictions on policy interactions.

## 4.1 Conceptual Framework: Policy Background, Tax Interactions and Investment

Flaring and venting alter static farm productivity. These one-period effects bring about a dynamic response because farmers' investment incentives change as a consequence of intertemporal provisions in tax policy. Linking static to dynamic outcomes relies on the timing of realized taxation and investment de-

[22]Very few physiological mechanisms link contemporaneous flaring or venting to crop health in future periods. Air pollution uptake occurs through gas exchange via stomata, hence is contemporaneous (Kulshrestha and Saxena, 2016).

[23]Environmental economics often connects static environmental effects to economic behavior via channels such as averting expenditures or residential sorting. We add another mechanism related to firm behavior, namely how a static productivity shock interacts with the tax system to induce new investment.

cisions. Paying taxes is an end-of-period event, while investment is a start-of-period decision. Taxes are levied on period $t$ net revenues at approximately the same time that period $t+1$ investment is determined. This enables us to treat end of period $t$ and start of period $t+1$ as equivalent. This simple timing assumption, which matches how farms behave, combined with Canada's tax code is all that is needed to link static physiological to dynamic economic outcomes.

Investment, in our analysis, means adding land and cultivating more acres. Land is easily the most important asset in our setting. For context, Alberta's annual cost and return benchmarks highlight that spending on land accounts for 75% or more of farm investment (Alberta, 2024*a*).[24]

Tax interactions emerge from section 30 of the Canadian *Income Tax Act*. Section 30 is titled "Improving land for farming." It states "there may be deducted in computing a taxpayer's income for a taxation year from a farming business any amount paid by the taxpayer before the end of the year for clearing land, levelling land or installing a land drainage system for the purposes of the business, to the extent that the amount has not been deducted in a preceding taxation year" (Canada, 2024*a*). Put differently, section 30 allows full same-year expensing of investment in farmland, creating strong incentives for farmers to expand their operations to offset tax payments in response to positive income shocks. Section 30 is a non-refundable deduction, which introduces an asymmetry: the effect on the upside is not mirrored on the downside. Positive and negative surprises have different effects, and a negative productivity shock such as one related to venting does not generate equivalent incentives (relative to an all else constant counterfactual) as an increase in income.

Section 30 embeds an important subtlety with respect to timing, one that we exploit to show how a static environmental shock generates dynamic economic responses. It is the timing that creates the tax interaction. Tax savings are related to realized period $t$ profits, while investment refers to production next period, in $t+1$. Investment decisions are about the future but the policy interaction arises because of the past. That is, the incentive for investment in period $t+1$ is caused by an after-the-fact tax benefit from period $t$. Figure 3

[24]Further, while investment in machinery may be an important margin in developing economy settings, in Alberta most farms are already sufficiently mechanized to accommodate the economic scope of land investment in this analysis. For example, an existing farm that expands by 10 acres is unlikely to add another combine.

provides intuition for the static-dynamic interaction, illustrating the intertemporal connection between flaring and venting and farm investment. Appendix E contains a model that formalizes the farmer's decision problem, highlighting how section 30 changes the first-order condition on investment.

The set-up for Figure 3 is straightforward and proceeds in three steps. First, the farmer selects the amount of land to cultivate in season $t$. This is given by $A_t$. This decision is based on expected marginal productivity, where expected marginal productivity is given by $\mathbb{E}[F_A(A_t;\theta)]$. $F_A(A_t;\cdot)$ is the derivative of the production function (i.e., marginal product) and $\theta$ is expected productivity per acre.

Acres, $A_t$, are determined by equating expected marginal revenue product (output prices are normalized to one) from farming to the user cost of land (i.e., the rental rate). This is shown as point $a$ in Figure 3. Critically, acres are selected before productivity is known, so are fixed for the period. This timing assumption is natural and closely matches how decisions are actually made.

In the next step, productivity is realized and the farmer earns returns. Figure 3 illustrates the situation where flaring increases crop yields, so realized productivity in period $t$, given by $\tilde{\theta}_t$, exceeds the initial expectation, $\theta$. Higher productivity also implies that the realized marginal productivity of land curve, $F_A(A_t;\tilde{\theta}_t)$, sits above the expected marginal productivity curve, and that the realized rate of return exceeds $r$, the start-of-season rental price per acre.

The final step involves settling tax accounts at the same time as period $t+1$'s land input is chosen. This is where the policy interaction enters. Ignoring section 30, a positive productivity shock due to flaring brings an unexpected additional tax payment equal to $\tau \cdot \left[F_A(A_t;\tilde{\theta}_t) - \mathbb{E}[F_A(A_t;\theta)]\right]$, where $\tau$ is the tax rate.[25] This unexpected tax payment reduces the benefits from the positive yield surprise as some of the upside is shared with the government. Still, even with taxes, the rate of return from farming $A_t$ acres would still exceed $r$, but less so than if there was no taxation. Rather than being located at point $a$, the realized net-of-tax outcome would be at point $b$ in Figure 3. (To reduce clutter, we do not show a net-of-tax, ex section 30 realized marginal productivity curve,

[25] Farmers pay a series of taxes, including corporate, dividend and personal income taxes. At the same time, they have access to an array range of deductions. We treat $\tau$ as an effective marginal tax rate (Fullerton et al., 1999) that combines the myriad taxes and credits.

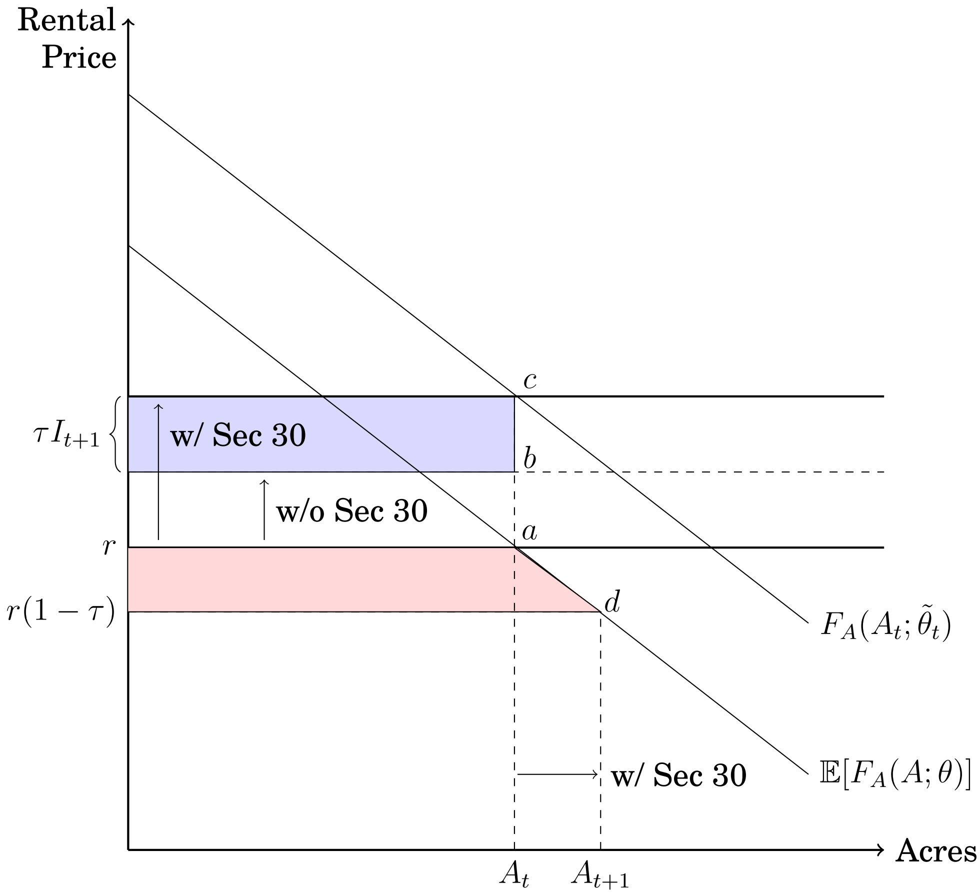



Figure 3: Farm Investment with Intertemporal Tax Policy Interactions

but it would sit between the two curves, cutting the dashed, vertical $A_t$ line at point $b$.) Without section 30 of the *Income Tax Act*, flaring generates higher than expected returns and larger than expected tax payments, but the static shock does not induce a dynamic policy interaction.

Section 30 leads to two effects. First, as shown in the Figure, it reduces period $t$'s tax burden by an amount equal to $\tau I_{t+1}$, where $I_{t+1} = A_{t+1} - A_t$ is investment in land. Investment is inherently dynamic. Investment also increases realized after-tax returns in period $t$. Point $b$ in Figure 3 shifts to $c$. Second, investment means that the farm grows: $A_{t+1}$ acres are farmed in the next period, even though, absent section 30, *counterfactual optimal farm size remains unchanged*.[26] This is the tax policy interaction. Flaring increases realized returns

[26]That is, without the tax benefits, the farm would choose $I_{t+1} = 0$ setting $A_t = A_{t+1}$. Ap-

in period $t$. To offset the additional tax payment associated with higher than expected returns, farmers leverage section 30 deductions. These deductions increase acres farmed in $t+1$ even if the surprise productivity shock is expected to last for only a single period. There is a dynamic response to the static shock. Past outcomes influence future decisions because of specific features of the policy environment and the pollution spillover.

This result is very much in the spirit of Hall and Jorgenson (1967). Section 30 reduces the user cost or rental price of land by last period's tax rate, $\tau_t$. Farmers trade-off higher after-tax returns in period $t$ with lower marginal productivity in period $t+1$.[27]

Critically, this tax interaction mechanism, driven by straightforward timing assumptions, helps us understand the link between static and dynamic environmental shocks and yields five predictions that are testable with our data. Measuring and testing these are the focus of remainder of the paper. The predictions are:

- The first prediction is obvious. The model predicts that farm sizes will expand in the period following a flaring productivity shock *but* that expansion is not attributable to a fundamental change in the value of the land. Expansion is exclusively due to a tax deduction, a temporary change in the after-tax rental price per acre. The pre-section 30 rental price per acre, $r$, does not change. Section 3.2 demonstrated that flaring and venting are unrelated to land prices. What remains is to show that additional acres are cultivated following exposure to a flaring spillover, namely that $A_{t+1} > A_t$. [Prediction 1]

- Second, negative shocks that cause a reduction in yields, such as the those associated with venting, should not affect investment. There are no tax advantages to lower than expected returns. That is, a negative surprise leads the farm to save expected taxes equal to $\tau_t\big[F_A(A_t;\tilde{\theta}_t) - \mathbb{E}[F_A(A_t;\theta)]\big]$, so relative to a counterfactual without venting there is no incentive for excess investment. As a result, we predict an asymmetric response from

pendix E formalizes this.

[27] This trade-off is visible as the colored areas in the figure. The shaded blue area illustrates the tax advantages of section 30, while the shaded red area illustrates the costs.

positive and negative productivity effects. Flaring will lead to expansion, while there will be no meaningful change in farm size associated with venting. [Prediction 2]

- Third, the marginal revenue product curve, $F_A$, is downward sloping, so average per acre farm productivity should be lower in period $t+1$ compared with the prior year. Farmers bring lower quality land into cultivation on the margin.[28] Therefore, a negative correlation between farm expansion and average productivity per acre should be observed. [Prediction 3]

- Fourth, absent meaningful adjustment costs, expansion should be short-term. Once period $t$ tax benefits are exhausted, the farm should return to its optimal size, $A_t$ acres, in future periods. In other words, conditioning on future flaring exposure should make expansion temporary (unless there are sizeable adjustment costs). This is because the only reason for the dynamic response is the policy interaction. If optimal farm size is $A_t$, the farm should return to that size once the tax advantages are exhausted. We do not make any prediction with respect to the magnitude of adjustments costs and leave it as an empirical question. [Prediction 4]

- Finally, the fifth prediction is that there is nothing special about flaring. Dynamic responses in our setting arise because a static pollution spillover interacts with the Canadian *Income Tax Act*. Oil and gas production has unexpected and dynamic implications for proximate agriculture, however any positive shock – whether attributable to sulphur fertilization or, say, higher than forecast prices – should produce similar dynamics. Of course, the advantage in our setting is that we are able to leverage intertemporally varying and spatially precise data, something that is challenging with weather or prices. It also demonstrates how existing policies may have unintended effects when environmental conditions change, but a positive revenue surprise due to higher than forecast prices should produce similar dynamics. [Prediction 5]

As stated, the next sections test these five predictions. However, it is worth

[28] The comparative static determining the trade-off of tax benefits relative to lower marginal productivity depends on the slope of $F_A$ and is given by $\frac{dA}{d\tau} = \frac{r}{F_{AA}}$.

explaining why we do not directly work with farm-level tax data. First, farm tax payments occur after accounting for a complex set of corporate, small business, and personal rates and credits. Canadian personal tax rates are characterized by progressive provincial and federal schedules. Beyond needing to map the tax returns of individual household members to the farming operations, credits have a range of arbitrary eligibilities and clawbacks. Determining the effective marginal tax rate on a farm-by-farm basis is non-trivial and would require information on the individualized tax returns of each farm, in each year, of our dataset. This poses notable empirical challenges. To start, it implies that $\tau$ is a time-varying function of overall household and farm income. More importantly, due to privacy concerns, the Canada Revenue Agency was unwilling to grant access to farm-level tax information, even to sworn employees of the government. Even with this information, however, it is not clear that accurate farm-level effective tax rates could be generated with an acceptable degree of error. Based on conversations with government officials, it may simply not be possible to obtain effective marginal tax rates for specific farms. For these reasons, we work with predictions from the model rather than observation-specific tax rates.

## 4.2 Dynamic Econometric Specification: Local Projections

Policy interactions imply that shocks at time $t$ may persist, propagating over multiple periods. Conventional methods in environmental economics typically assess multi-period effects by estimating event study models or through adding model structure. Both of these approaches are ill-suited to this context. Event studies are fundamentally static. That is, event studies target a different estimand than the one in which we are interested. They aim to recover the static treatment effect, sketching how that static effect changes in different periods. We are interested in the *dynamic path* of the dependent variable, because investment implies dynamics that are both backward and forward looking. Investment is backward looking because of the nature of the stock variable, farm size, and forward looking because of the role of expectations. At the same time, we seek to maintain the flexibility of the event study design as we are interested in both the role of stock dynamics and expectations. Our conceptual framework avoided making specific assumptions about adjustment costs, because our goal is to allow our estimates to capture these dynamics.

Capturing dynamic effects naturally suggests an impulse response function. Our objective is to trace the time series path of our outcome variable following a shock. To estimate these propagation paths requires a method akin to event studies – retaining much of the identification intuition from the static setting – but requires an estimator that flexibly captures the time series features of the question. We use local projections (Jordà, 2005). Local projection is applied extensively in macroeconomics to estimate the dynamic effects of macroeconomic shocks (i.e., to generate univariate impulse response functions). Recently, local projection has moved to microeconomic settings, such as ours, where understanding dynamic treatment effects is equally important (see, e.g., Roth Tran and Wilson, 2023; Berg, Curtis and Mark, 2023; Dube et al., 2023; Colmer, Evans and Shimshack, 2023).

The appeal of local projections is parsimony and robustness to misspecification: it allows for time series dependencies without fully specifying a multi-equation data generating process. The method estimates farms' dynamic investment responses to flaring and venting shocks, while flexibly controlling for the investment process. In our context, local projections predict the outcome of interest, farm size, over different time-horizons, relative to a shock (flaring and venting exposure) that occurs in a base period.[29] We approach the propagation of shocks two ways, as we outline below.

First we estimate the effect of exposure in a base period without conditioning on future values of flaring and venting. This specification corresponds with our first and second predictions. By omitting future values, we incorporate the positive probability that current period exposure is followed by additional exposure in subsequent periods (Jordà, 2023). We use this as our initial approach, as by excluding future exposure we estimate the cumulative impact response caused by the shock. Stated differently, we do not sterilize the estimand of anticipation, expectations, or potential adaptation following the initial shock, highlighting one of the ways that local projections differ from more conventional event studies. Expectations are an important element of economic activity, and farmers may change the timing of decisions as a response to the shock. We want

[29]Linear projections require linearity, stationary and conditional independence of shocks, conditions that plausibly hold in this setting.

to capture the impact over a series of periods, net of the economic responses of farmers.

In Section 4.3.3, we present our second approach that aligns with our fourth prediction, isolating the effects of a one-time exposure. We do so through both identifying large and unanticipated increases in flaring and venting and conditioning on future exposure. This model is more akin to a standard event study. Both approaches have an advantage unique to our setting. As both flaring, a positive shock, and venting, a negative shock, are included within the same model, this enables us to explore asymmetric propagation (i.e., Prediction 2).

Both approaches define $t-1$ as the base period. The model then captures the effect of flaring and venting exposure in year $t-1$ on farm investment over different horizons, from $t$ to $t+H$. Our preferred results estimate horizons up to $H=3$, four years post exposure, or approximately one-quarter of our panel length. Importantly, we condition on the farm's size in year $t-1$. As Jordà (2023) describes, including a lagged dependent variable has two advantages. First, it acts as a sufficient statistic for previous interventions. In our setting, this means that we are capturing current period flaring and venting on farm size, controlling for historical deposition and adjustment. Second, including a lagged dependent variable enables us to use conventional clustered standard errors without requiring Newey-West-style autocorrelation terms (Montiel Olea and Plagborg-Møller, 2021). We work in a panel setting with farm fixed effects and a short panel, however. The cost of including lagged acres is Nickell bias (Nickell, 1981).[30] To circumvent this, we adopt the approach of Blundell and Bond (1998) and estimate a system-GMM variant of each regression with the endogenous lagged variables instrumented with deeper lags in both levels and differences, including lags of up to four periods as instruments.[31]

This first specification, without sterilizing for future values, involves estimating a series of $H$ separate regressions:

$$\begin{aligned}\Delta^h \text{Acres}_{it} =& \alpha_f^h \text{Flare}_{it-1}^{50km} + \alpha_v^h \text{Vent}_{it-1}^{50km} + \mu^h \text{Acres}_{it-1} \\ &+ \boldsymbol{W_{it-1}^{h\prime}} \boldsymbol{\theta} + \rho_i + \gamma_t + e_{it+h} \qquad h = 0, 1, 2, ..., H,\end{aligned} \tag{3}$$

[30]Nickell bias is also a concern in local projections without a lagged dependent variable unless the panel's time dimension is sufficiently large (Herbst and Johannsen, 2021). Our panel is short relative to many local projections, so addressing this bias is important in our setting.

[31]Results are robust to adopting different lags as instruments.

where the dependent variable, $\Delta^h \text{Acres}_{it} = \text{Acres}_{it+h} - \text{Acres}_{it-1}$, is investment by the farm over the horizon, measured as the change in acres planted by farm $i$ in year $t+h$ relative to the base period $t-1$.[32] In (3), $\text{Flare}_{it-1}^{50km}$ and $\text{Vent}_{it-1}^{50km}$ capture the total flaring and venting activity, respectively, that occurs within a 50km radius of the farm (excluding flaring and venting activity that occurs within a 5km buffer surrounding the farm's centroid) in the base period. The variable $\text{Acres}_{it-1}$ controls for the farm's total acreage in the base period, which is the stock variable; $\rho_i$ and $\gamma_t$ are farm and year fixed effects, while $\boldsymbol{W_{it-1}^h}$ is a vector of controls for weather conditions in the base period.[33]

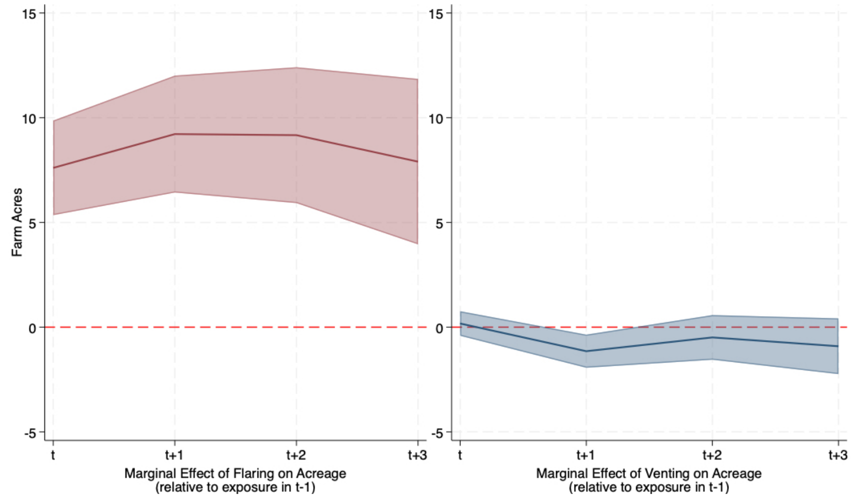
The coefficients of interest are $\alpha_f^h$ and $\alpha_v^h$, which reflect the change in farm acreage due to a one mcm change in flaring or venting exposure within a 50 km radius of the farm, $h$ years after exposure occurs. These represent the farm's dynamic response to a temporary pollution shock. Stated differently, pollution exposure occurs in year $t-1$. This pollution is temporary, occurring in that specific year. $\alpha_f^h$ corresponds to prediction one from our conceptual framework. Given the policy interaction, we expect it to be positive and economically meaningful. $\alpha_v^h$ tests the second prediction. The conceptual framework predicts a null dynamic response to venting.

Identification in (3) requires several conditions. Identical to the static analysis, conditional on weather, changes in flaring and venting exposure must be uncorrelated with unobserved productivity shocks (such as changes in fertilizer prices and other sources of pollution) and changes in crop prices. We also maintain the standard Blundell-Bond assumption that changes in deeper lags of farm size are uncorrelated with the farm fixed effects. As above, it is unlikely that flaring and venting are correlated with unobserved productivity shocks. (The evidence in Section 3.2 is again directly relevant in supporting this claim.)

[32]Our acreage measure incorporates fallow periods (when no acres are planted), so this variable cannot be log-transformed. To account for potential outliers, we winsorize farm acreage at the 1% level in all regressions.

[33]These are identical to the controls in (1). They include monthly precipitation levels, a quadratic in growing season humidity, and the number of hours per growing season that farms are exposed to temperatures in one-degree bins from zero to forty degrees Celsius.

Figure 4: Dynamic Investment Response to Flaring and Venting Exposure




*Notes:* Figure shows point estimates and 95% confidence intervals for the local projection analysis outlined in Equation 3. The left inset shows the effect of flaring and the right inset the effect of venting. The dependent variable is the change in total acreage planted over the horizon relative to year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level.

## 4.3 Dynamic Results

### 4.3.1 Predictions 1 & 2: Investment Response to Flaring and Venting

Our results reveal an asymmetric investment response to flaring and venting, matching predictions one and two. Farmers respond to the positive productivity shock created by flaring by increasing farm size, but have no response to the negative venting shock. Policy interactions resulting from static pollution effects from oil and gas induce dynamic investment responses in agriculture.

Results are presented in Figure 4 and Table 4. Exposure to flaring and venting occurs in period $t-1$. Figure 4 plots the coefficient estimates and 95% confidence intervals for flaring (left panel) and venting (right panel) exposure for each horizon, one year to four years after exposure. Table 4 reproduces the coefficient estimates as well as the coefficient estimates on lagged acreage. Results are for total acres planted. Standard errors are clustered by farm to account for serial correlation in farm investment.

Figure 4 and Table 4 show that farms exposed to flares cultivate an additional 7.6 acres of land per mcm of exposure in the year following exposure. This remains relatively consistent over our four year horizon. The average farm size

Table 4: Dynamic Investment Response to Flaring and Venting Exposure

| | (1)<br>$\Delta$Acres | (2)<br>$\Delta^1$Acres | (3)<br>$\Delta^2$Acres | (4)<br>$\Delta^3$Acres |
|---|---|---|---|---|
| $\text{Flare}^{50}_{i,t-1}$ | $7.61^a$ | $9.22^a$ | $9.17^a$ | $7.90^a$ |
| | (1.15) | (1.42) | (1.66) | (2.02) |
| $\text{Vent}^{50}_{i,t-1}$ | 0.18 | $-1.15^a$ | -0.49 | -0.91 |
| | (0.30) | (0.40) | (0.54) | (0.68) |
| $\text{Acres}_{i,t-1}$ | $-0.08^a$ | $-0.08^a$ | $-0.11^a$ | $-0.04^b$ |
| | (0.01) | (0.01) | (0.02) | (0.02) |
| $N$ | 184410 | 161990 | 141998 | 124106 |

*Notes*: Dependent variable is the change in total acreage planted over the horizon relative to year $t-1$, with horizons ranging from $t$ (column (1)) to $t+3$ (column (4)), respectively. Flare and vent treatment variables are defined at the 50km radius (less a 5km buffer around the farm) and are measured in the base year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level. Significance at the 1%, 5%, and 10% levels are denoted by $^a$, $^b$, and $^c$, respectively.

in our sample is 1,039 acres. Exposure to an average flaring shock of approximately 4 mcm leads to an economically meaningful expansion of roughly 3% within four years versus a counterfactual scenario where the farm was not exposed to a flare. This is a notable finding, as other forms of industrial activity have the potential to create similar positive pollution spillovers for agriculture, as in Sanders and Barreca (2022).

To place these estimates in the context of our conceptual model, we can combine our regression estimates with additional information to calculate an implied tax rate for an average farm. Let the average farm in Alberta be 1,039 acres and assume that it only grows wheat. Table 1 shows that the average yield for wheat is 1282.5 kg per acre and that the average farm is exposed to 3.8 mcm of flaring. Assume a price per kg of wheat of \$0.40 CAD and that a new acre of wheat requires \$750 to enter into production (Alberta, 2024*a*). Using the estimates from Tables 2 and 4 implies an effective tax rate 48.8% would justify the observed expansion.

A marginal effective tax rate of 48.8% aligns with estimates from the literature. McKenzie (1994), for instance, estimates marginal effective tax rates for Canadian agriculture, forestry and fishing of between 44.6%-50.2%. In the US, Li and Pomerleau (2020) estimate that the 2017 marginal effective tax rate on farm land equalled 39.2%. This estimate is also close to Canada's top combined federal plus provincial personal income rate of 48% of 2017 (Canada, 2024*b*).[34]

As predicted, the venting response is starkly different. Figure 4 and Table 4 show precisely estimated zeros. Investment does not respond to venting. When oil and gas facilities release uncombusted associated gases, agriculture producers experience a negative yield shock. There is no policy interaction – no tax benefit – with a negative surprise, so farmers maintain the steady state. Moreover, the flaring and venting paths are from the same set of regressions and are thus internal to the model. This means that venting acts as an internal placebo for flaring and vice versa, adding notable credibility to the estimates.

The asymmetric paths indicate startlingly and interesting economic behaviour. Principally, there is a dynamic response to a transitory environmental shock. Equally important, however, is that the nature of the shock – i.e., a positive versus negative revenue surprise – induces very different behavior as a consequence of the policy interaction. These patterns would be challenging to recognize with an event study framework, where one would observe either a positive or negative shock in isolation. In Online Appendix F, we extend these results along a few dimensions. First, we show that the expansion is almost entirely in cash crops. Second, we show that dynamics in Figure 4 likely extend beyond four periods post-exposure.

#### 4.3.2 Prediction 3: Farm Expansion Affects Yields

Flaring combined with policy interactions cause farms to expand. An implication of expansion – Prediction 3 of our conceptual framework – is that farm expansion should reduce yields, conditional on the main determinants of crop productivity. This is a byproduct of the farm's optimization problem. If farms are making optimal investments, then an expansion without a change in underlying productivity should be onto less productive acres. As such, average yields should be negatively correlated with expansion.

[34]To reiterate, individual tax rates depend on many variables including non-farm income, other investments, tax credits, province of residence and year.

We test this prediction with the following regression:

$$\ln(\text{Yield}_{it}) = \omega\Delta\text{Acres}_{i,t-1} + \beta_1\text{Flare}_{it}^{50km} + \beta_2\text{Vent}_{it}^{50km} + \boldsymbol{W_{it}\theta} + \rho_i + \gamma_t + \epsilon_{it}, \tag{4}$$

where $\Delta\text{Acres}_{i,t-1}$ is the farm's growth rate from the previous period[35] and all other variables are as defined in (1), including time and farm fixed effects which control for prevailing prices and farm-specific factors. In (4), the coefficient $\omega$ is the correlation between the farm's growth rate and their subsequent yield, conditional on weather, flaring, and venting. A positive correlation indicates the farm's average yield increases following expansion, whereas a negative correlation indicates a decrease in the farm's average yield following expansion.

The results of this regression are presented in Table 5. Farm expansion leads to lower productivity for each of barley, canola and wheat; all three crops show a negative correlation between farm expansion and yields. The results for wheat, for example, show that a doubling in farm size is correlated with a 1.5% reduction in average wheat yields. The corresponding estimates for barley and canola are a 1.7% reduction and a 0.9% decrease. Coefficients are precisely estimated at conventional levels.

Table 5: Effects of Past Farm Expansion on Agricultural Yields

| | (1) Barley | (2) Canola | (3) Wheat |
|---|---|---|---|
| $\Delta\text{Acres}_{i,t-1}$ | -0.017$^a$ | -0.009$^b$ | -0.015$^a$ |
| | (0.005) | (0.004) | (0.003) |
| $N$ | 86203 | 104358 | 108040 |

*Notes*: Table shows the results of a regression of the natural log of crop yields on the percentage change in farm size in the previous period ($\Delta Acres_{i,t-1}$). Yields for barley, canola, and wheat are shown in columns (1) to (3), respectively. All regressions include linear controls for flaring and venting exposure, month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level. Significance at the 1%, 5%, and 10% levels are denoted by $^a$, $^b$, and $^c$, respectively.

[35] To preserve years where the farm is fallow, we define this growth rate as $\Delta\text{Acres}_{i,t-1} = 2(\text{Acres}_{i,t-1} - \text{Acres}_{i,t-2})/(\text{Acres}_{i,t-1} + \text{Acres}_{i,t-2})$.

### 4.3.3 Prediction 4: Isolating One-Period Responses

So far, our results demonstrated the effect of the entire treatment path associated with flaring and venting on agricultural investment. The conceptual framework also suggests that in the absence of adjustment costs policy interactions should manifest differently in the case of a one-time exposure. Here, we attempt to isolate the response to a one-time exposure.[36]

Unfortunately, there are important econometric hurdles. We cannot simply include controls for future flaring and venting levels in (3). In (3), we address Nickell Bias in by using deeper lags of the treatment and control variables as instruments in a GMM estimator. This is invalid in this context. Including a sequence of treatments would entail that the instruments for future exposure would themselves be controls. To overcome this difficulty, we estimate a variant of (3), where we isolate large and unanticipated increases in flaring and venting and then condition on future exposure. This specification produces a distinct estimand relative to (3) for two reasons. By controlling for future exposure, we trace the farm size propagation path for exposure in $t-1$ net of correlated future exposure. This is what we need to assess prediction four. However, by focusing on large increases in flaring and venting, our estimand shifts from capturing the effect of a one mcm increase in exposure at the midpoint of the exposure distribution to the effects of a one mcm increase at the right tail of the exposure distribution. Tail investment responses may be different if there are non-linear effects. Notwithstanding the absence of strict equivalency across models, this set-up does allow us to assess prediction four of our conceptual framework.

To implement this alternative specification, we construct measures of tail flaring and venting shocks. A tail flaring shock is defined for farm $i$ in year $t$ if flaring volumes in $t$ are more than double their average levels for $i$. We capture these shocks with the variable $\tau_{it}^{F}$, which equals zero for all farm-years where flaring volumes are less than double the farm's average and equals the size of the shock for all farm-years where flaring volumes are more than double the farm's average. $\tau_{it}^{V}$ is defined similarly for venting. The primary sources of flaring and venting shocks are non-routine (i.e., emergency) flaring and venting and

[36] We do not observe adjustment costs directly. Therefore, evidence can only support our conceptual framework but cannot invalidate it. Still, demonstrating one-period reversion is consistent with our conceptual framework.

excessive flaring and venting in the first months after a well is drilled[37]. When constructing $\tau^F_{it}$ and $\tau^V_{it}$, we are agnostic to the specific source of abnormally high levels of emissions and simply rely on the fact that they represent a large but short lived increase in exposure. Of course, we still require the assumption that these shocks are exogenous to other determinants of crop productivity.[38]

To estimate this model, we replace the flaring and venting exposure variables in (3) with $\tau^F_{it-1}$ and $\tau^V_{it-1}$. We also include controls for future flaring and venting that occurs over the horizon, lagged acreage, and weather controls. All controls are also interacted with the farm's treatment status. Prediction four is ultimately tested with the following regression:

$$\begin{aligned}\Delta^h \text{Acres}_{it} = \alpha^h_f \tau^F_{it-1} + \alpha^h_v \tau^V_{it-1} + \sum_{j=0}^{h-1} \boldsymbol{\delta}^j_f \text{S}_i \text{Flare}^{50}_{it+j} + \sum_{j=0}^{h-1} \boldsymbol{\delta_v}^j \text{S}_i \text{Vent}^{50}_{it+j} \\ + \boldsymbol{\mu^h} \text{S}_i \text{Acres}_{it-1} + \text{S}_i \boldsymbol{W^{h'}_{it-1}} \boldsymbol{\theta_v} + \rho_i + \gamma_t + e_{it+h} \qquad h = 0, 1, 2, ..., H.\end{aligned} \tag{5}$$

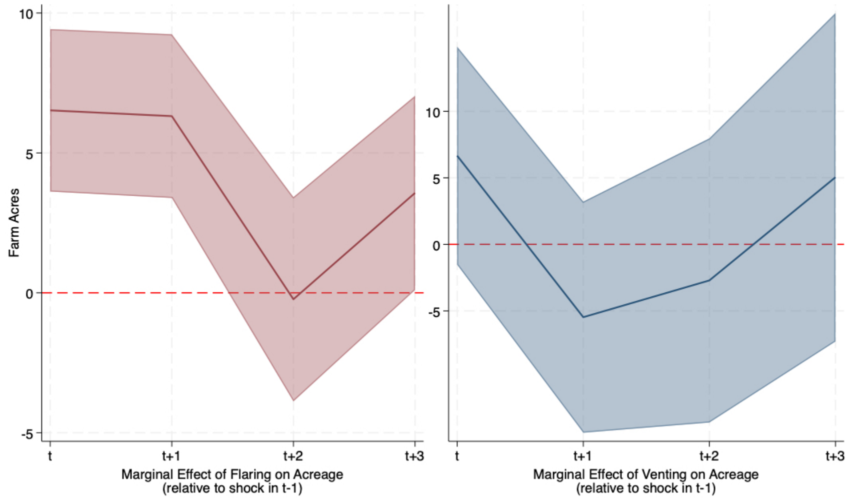
where the inclusion of $\text{Flare}^{50}_{it}$ and $\text{Vent}^{50}_{it}$ control for the farm's exposure to both flaring and venting that occur during the horizon of interest after the base period. $\alpha^h_f$ and $\alpha^h_v$ show the effect of tail flaring and venting shocks on farm investment in period $h$, net of future exposure that happens over the horizon.

Results for this alternative specification are shown in Figure 5. This figure plots the change in total acres planted exclusively as a result of a period $t$ shock. The pattern mimics that of Figure 4 in the first two periods following the change. As the tax interaction dissipates, though, distinct dynamics appear. Three and four years post flaring shock, the magnitudes of the flaring shock coefficients shrink relative to those estimated in Figure 4. Three years post shock, the coefficient is both statistically significantly smaller than the corresponding estimate in Figure 4 and not statistically significantly different from zero. The coefficient four years post shock, while also not statistically significantly different from zero is not significantly different than the corresponding estimate in

[37]Alberta Directive 060 allows for much higher flaring and venting rates in the first six months of extraction.

[38]In Online Appendix F, we show an event study of farm exposure before and after the farm is exposed to a shock. Both flaring and venting growth rates show no meaningful pattern prior to a shock, a dramatic increase in the year of a shock, a dramatic decrease the year following the shock, and then level off at pre-shock levels.

Figure 5: Investment Response to a One-period Flaring and Venting Shock




*Notes:* Figure shows point estimates and 95% confidence intervals for the local projection analysis outlined in Equation 5. The left inset shows the effect of a flaring shock in $t-1$ (defined as a doubling in the amount of flaring within 50km of the farm) and the right inset the effect of a venting shock. The dependent variable is the change in total acreage planted over the horizon relative to year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects, with controls allowed to vary by farm treatment status. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level.

Figure 4. This evidence suggests farms may reverse their initial investments, which would be consistent with low investment adjustment costs. We caution, however, that the lack of precision in these estimates, paired with our inability to observe adjustment costs, leaves us unable to say with confidence that the persistence observed in Figure 4 would disappear if flaring was truly transitory. Controlling for future exposure causes the venting estimates to become noisier, but without any meaningful pattern relative to the baseline results.

#### 4.3.4 Prediction 5: Investment Response to Crop Prices

Our primary interest is how environmental spillovers link static pollution effects to dynamic economic responses. To this point, we have emphasized how flaring and venting change investment incentives. Yet, our mechanism, section 30 of the tax code, applies to any positive income surprise. This is the the final prediction in our conceptual framework. Adding this fifth prediction broadens the scope of this analysis beyond the spillover from oil and gas to farming to test the basic tax interaction mechanism.

Studying non-environment shocks poses several empirical challenges, however. Notably, we lose farm-specific variation. Thus, omitted variables and simultaneity are more likely. Nonetheless, we explore the basic mechanism, where returns are realized at the end of period $t$ and investment is made at the start of period $t+1$, using a constructed measure of seasonal crop price shocks.

We proceed as follows. We collect prices for Albertan wheat, canola and barley for August and September, typical harvest months. Farm-level variation is then obtained using acreage-weighted average crop prices calculated as:

$$\text{Farm Price}_{it} = s_{it}^{wheat}\text{Price}_t^{wheat} + s_{it}^{canola}\text{Price}_t^{canola} + s_{it}^{barley}\text{Price}_t^{barley}$$

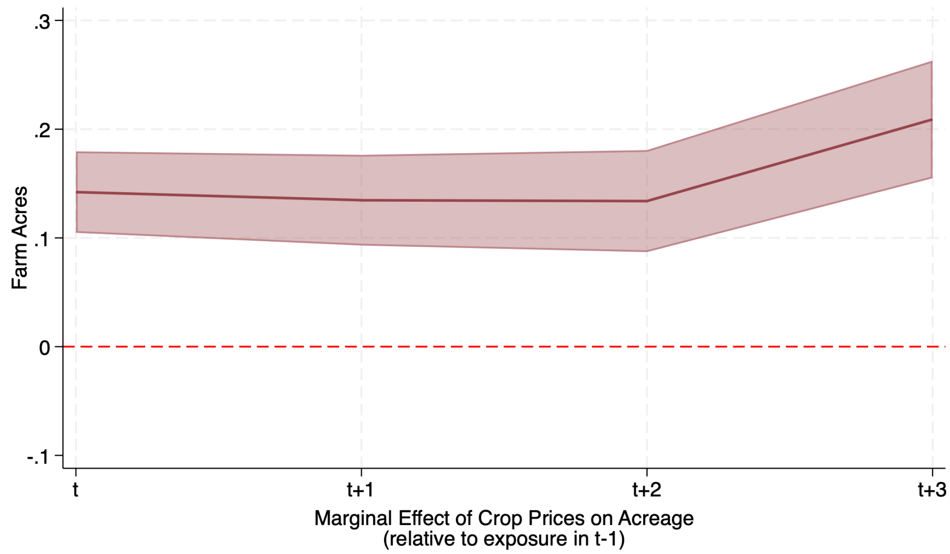
where $s_{it}^{j}$ is the share of total cash-crop acreage devoted to crop $j$, wheat, canola and barley. Differences within farm crop shares enables the variable Farm Price$_{it}$ to vary across farms within a given year. It also varies within farms over time because of intertemporal changes in crop shares and crop prices, for example, because of crop rotation schedules.

Ultimately, we use Farm Price$_{it}$ as a farm-specific, intertemporally-varying variable to test Prediction 5. Using Farm Price$_{it}$ poses several challenges, however. To start, commodity-specific prices are largely common across producers. Including time fixed effects leaves little residual variation. Further, farmers form expectations about seasonal prices that influence decisions, and it is possible to hedge against unexpected prices shocks using forward and futures contracts.[39] Notwithstanding these complications, Farm Price$_{it}$ offers a complementary method to offer suggestive evidence for the policy interaction, one that does not rely on the flaring and venting data.

As elsewhere, we estimate a local projection model replacing the flaring and venting variables in (3) with the Farm Price$_{it}$ variable. Results are displayed in Figure 6. As with flaring shocks, a price shock yields higher cash flows (in this case due to higher prices rather than higher yields). Figure 6 demonstrates that the positive price shock produces a pattern very similar to that observed when farms are exposed to flaring. Farms experiencing a positive revenue shock, whether through prices or productivity, expand, supporting Prediction 5 of the conceptual model and providing corroborating evidence of policy interaction.

[39]For example, many farm organizations and governments provide regular price forecasts which influence planting decisions.

Figure 6: Investment Response to Crop Price Changes




*Notes:* Figure shows point estimates and 95% confidence intervals for the crop price local projection analysis. The dependent variable is the change in total acreage planted over the horizon relative to year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Acreage is winsorized at the 1% level.

# 5 Discussion and Conclusion

Despite an international push for methane regulations and an end to routine flaring, little is known about the economic implications of flaring and venting beyond their consequences for climate change. This paper studies the effect of flaring and venting from upstream oil and gas production on proximate agricultural enterprises, uncovering surprising static and dynamic results.

Using confidential crop insurance data and comprehensive regulatory data, we spatially link flaring and venting to agricultural production in the Canadian province of Alberta, a setting with significant oil and gas and farming activities. We demonstrate that unanticipated pollution from oil production causes contemporaneous changes in agricultural yields. Flaring *increases* yields for wheat, canola, and barley by between 0.3% to 0.7% per mcm of exposure, while venting *decreases* yields between 0.1% to 0.5% per mcm of exposure. We further show that the positive effects of flaring are in large part driven by sulphur-containing gases, with high-sulphur venting increasing wheat and barley yields and high-sulphur flaring resulting in even greater yield increases. Equally surprising is that there are dynamic implications from these static crop yield responses. In the years following exposure, farmers respond to the positive flaring shock by expanding the size of their farms, but do not respond to the negative venting shock. Using a stylized model of the farmer's decision problem, we show that these asymmetric results can be explained by a policy interaction where Section 30 of the Canadian *Income Tax Act* creates a strong incentive for investment in acreage in response to positive income shocks. We further show that such dynamics can arise from any positive revenue shock, with farmers increasing future period acreage in response to higher crop prices.

This intertemporal link between physiology and economic behavior highlights how environmental shocks can have lingering effects even after the stimulus has abated. More explicitly, both the static and dynamic spillovers demonstrate that care is required when crafting regulations and studying outcomes. Such cross-sector unintended consequences are commonly studied by economists, but this analysis highlights that we should not stop at cross-industry effects. The dynamic, within operation implications of interventions and market shifts must also be explored. [40]

[40]The climate change implications of flaring and venting bear mention, particularly in light of our surprising flaring results. Venting methane is unequivocally negative for both global climate and local agriculture. The local agricultural benefits from flaring are substantial, but still small relative to global climate damages. For example, aggregate flaring emissions in Alberta in 2019 equalled 733 mcm, which is equivalent to roughly 2.1 million $tCO_2e$ (this could vary substantially depending on average flare efficiency). At a modest social cost of carbon of \$100/$tCO_2e$, the global damage from 2019 emissions is approximately \$211 million. Ignoring the dynamic effects of flaring and focusing just on the static consequences (which would overstate benefits due to sub-optimal expansion), our estimates imply a per-farm revenue increase of approximately \$7,195 for the average farm in 2019. This amounts to roughly \$45 million in additional farm income in 2019. More importantly, comparing the positive and negative effects of flaring is misleading. It is not flaring that increases farm yields, but flaring of sour gas. It is a coincidence that Alberta has geological formations with high levels of $H_2S$. Indeed, the deeper insight from our analysis is to demonstrate the channels through which policy can intertemporally alleviate and exacerbate distortions, in response to idiosyncratic shocks.

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# A Regulatory Background

Globally, about 144 billion cubic meters (bcm) of associated gas was flared in 2021, in line with volumes estimated over the past decade (World Bank, 2022*a*). Estimates of associated gas venting are more elusive, since global flaring estimates have historically relied on satellites that leverage measurements of infrared light (World Bank, 2022*a*). Newly launched satellites have the capability to measure methane columns and therefore provide data for estimating venting activity, as has recently been done in the US (Pandey et al., 2019; Zhang et al., 2020).

In Alberta, Canada, flaring and venting are regulated by the Alberta Energy Regulator (AER). They approve construction and permit the testing and ongoing operation of upstream oil and gas activities, subject to requirements set forth in relevant regulations and directives. There are many specific regulatory requirements on the practices of flaring and venting. We outline a small handful.

Regulations treat flared and vented gas differently, and put in place specific restrictions for what is known as 'sour gas', or gas containing a certain concentration of hydrogen sulphide (H2S), an odorous and poisonous gas.

The AER's *Directive 060* sets requirements for the release of solution gases through venting, flaring, or incinerating by wells or other facilities in Alberta's upstream oil and gas industry. The requirements in *Directive 060* have evolved over time, incorporating recommendations from the Clean Air Strategic Alliance (CASA), a multi-stakeholder organization whose goal is to manage air quality in the province, and integrate the *Alberta Ambient Air Quality Objectives and Guidelines (AAAQO)* (Alberta Energy Regulator, 2022). More recently, the AER instituted further restrictions on venting as part of Alberta's efforts to reduce methane emissions in the upstream oil and gas industry. The new restrictions include site-specific limits for total vent gases and routine vent gases, with the option for crude bitumen batteries to meet the regulations through fleet-wide averaging (Alberta Energy Regulator, 2022).

*Directive 060* requires that wells whose combined flaring and venting exceeds 900 cubic meters per day must conduct an economic analysis of solution gas conservation; where the analysis determines a sufficient net present value, the gas-oil ratio is high, or the AER otherwise requires it, wells must be shut in until the have put in place controls designed to conserve 95% of solution gas, and conserve at least 90% on an ongiong basis.

Sour gases have historically been subject to more regulatory requirements due to the toxicity, flammability, and odour of H2S-containing gases. The *Oil and Gas Conservation Rules* require gases containing more than 10 moles per kilimole (1%) H2S be burned to convert virtually all of the H2S to sulphur dioxide. Further, the gases must be tested prior to flaring (and within 12 months of future flaring), and the gases must be flared in such a way that the ambient concentrations for H2S and SO2 do not exceed the limits set by the Alberta Ambient Air Quality Guidelines. These requirements are reiterated in *Directive 060*, which states that gases with 10 moles per kimole H2S cannot be vented, and the release rate of H2S from crude bitumen batteries cannot exceed 0.04 cubic meters per hour.

The *Oil and Gas Conservation Rules* and *Directive 060* also indicate the design requirements for flare stacks, while the *Oil and Gas Conservation Rules* further stipulate that gases must be burned such that visible smoke is limited. Setback requirements for flares (i.e., the minimum distance at which they may be constructed or operated from certain objects or geographical features) are indicated in the *Oil and Gas Conservation Rules*, which state that they cannot be within 100m of a "surface improvements, except a surveyed roadway" [S.8080(3)]; *Directive 060*, which restricts release of solution gases in excess of 900 cubic meters per day within 500m of a residence, and since 2000 restricts any flaring in this context; the *Forest and Prairie Protection Regulation* restricted burning of sour gas within a distance 2.5 times the flare stack height of any debris, and since 2017 restricts flaring of any gas within 30 meters of "any timber, vegetation, or combustible material"; and *Directive 056*, which outlines setback requirements for wells containing H2S gas, with 4 levels ranging from 0.1 to 1.5km specified depending on the release rate and type of nearby structures (e.g., permanent dwelling, urban environment).

# B Supplement Figures, Illustrating Patterns in the Data

The following includes a series of additional figures and notes on the data used in this analysis.

Figure B.1 shows the time series variation in flaring and venting volumes in mcm for seven census agricultural regions (CAR) of the province of Alberta. Notable cross-region and intertmeporal variation is apparent in both flaring and venting volumes.

Figure B.2 shows the distribution of flaring and venting across townships, with the vast majority having small volumes while a handful have much greater exposure. This reflects the fact that about 20% of reporting facilities are responsible for about 85% of flaring and venting volumes. The second and third panel show the distribution of flaring and venting, respectively, across Alberta townships, with lighter squares representing relatively higher average annual volumes; few squares are lighter, illustrating the skewness of the distribution.

Figure B.3 shows the degree to which flaring and venting activity and agricultural fields are co-located. To do so, the figure aggregates data to the township level (six-mile by six-mile grid tile), a coarser level than used in our analysis. Each township is then coded as being in one of three mutually exclusive categories. A township can have a farm and no flaring activity; it may have flaring but no farming; or both flaring and farming co-located within the township. Similar coding is completed for venting. The left panel of Figure B.3 is for flaring. Townships with only flaring are shown in pink. Townships with only farms are shown in green. Townships with both are sky blue. The right panel repeats the analysis for venting with the only venting status in pink. Farms remain green and townships with both are shown in sky blue. Figure B.3 shows the notable spatial variation for farming, flaring and venting in Alberta. Many farms are proximate to either flaring or venting, while others are distant.

Figure B.4 shows the distribution of total acreage for barley, canola and wheat for the period 2002 to 2019. Each point represents the acreage for a given field centroid over the period by crop type, with the size reflecting the relative acreage.

Figure B.5 shows the per farm exposure to flaring and venting for different

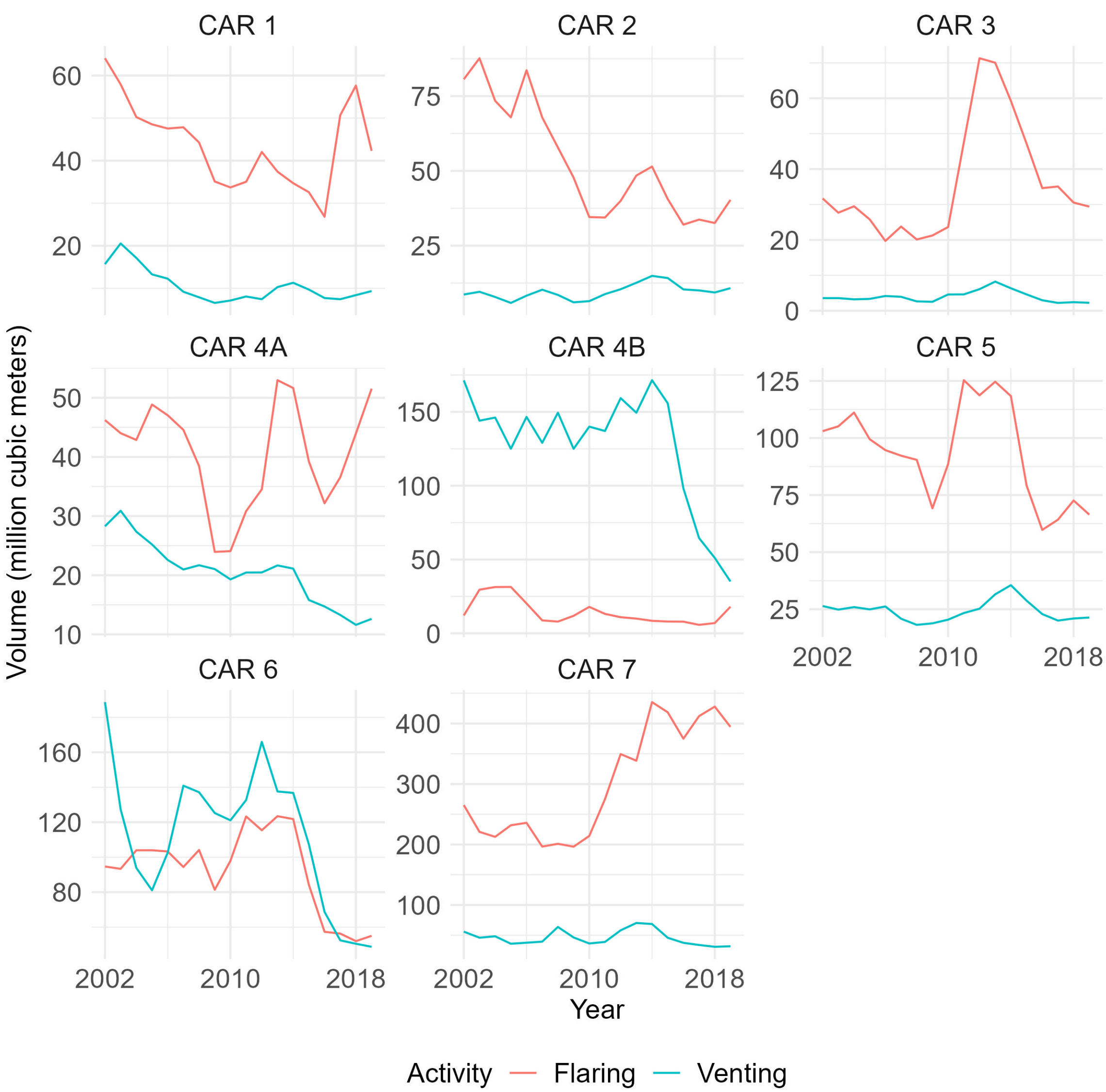



Figure B.1: Trends in flaring and venting activity in Alberta by Census Agricultural Region (CAR), 2002-2019

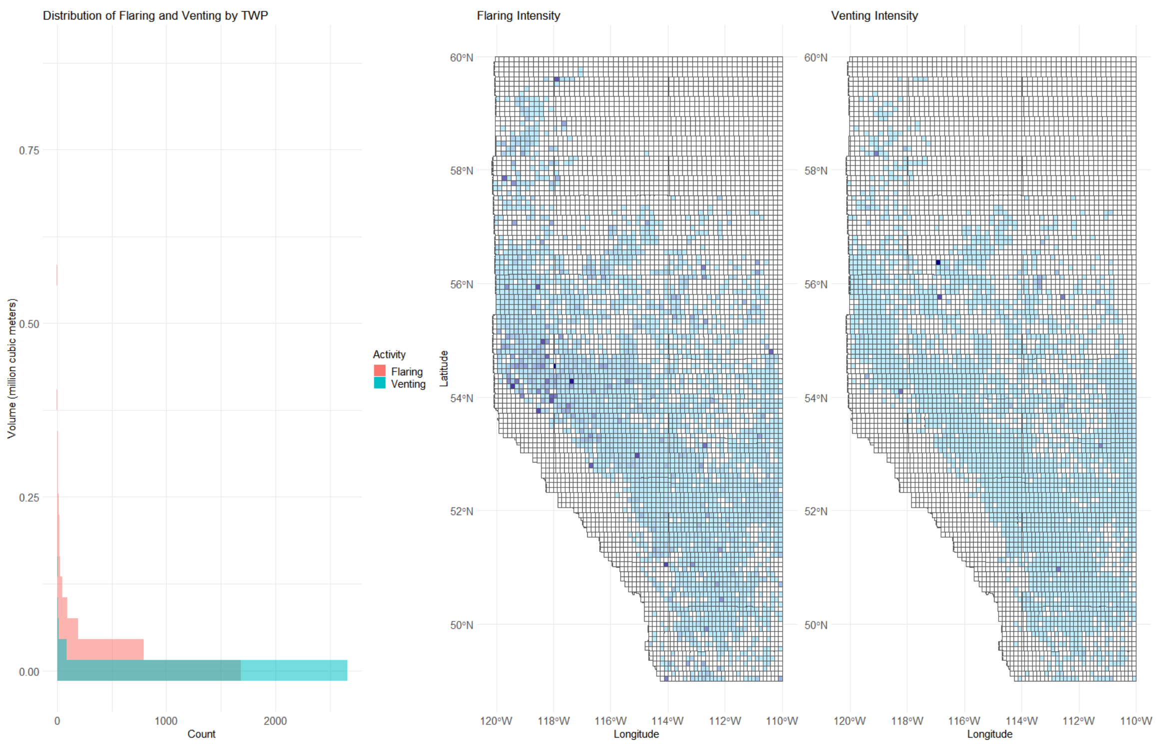
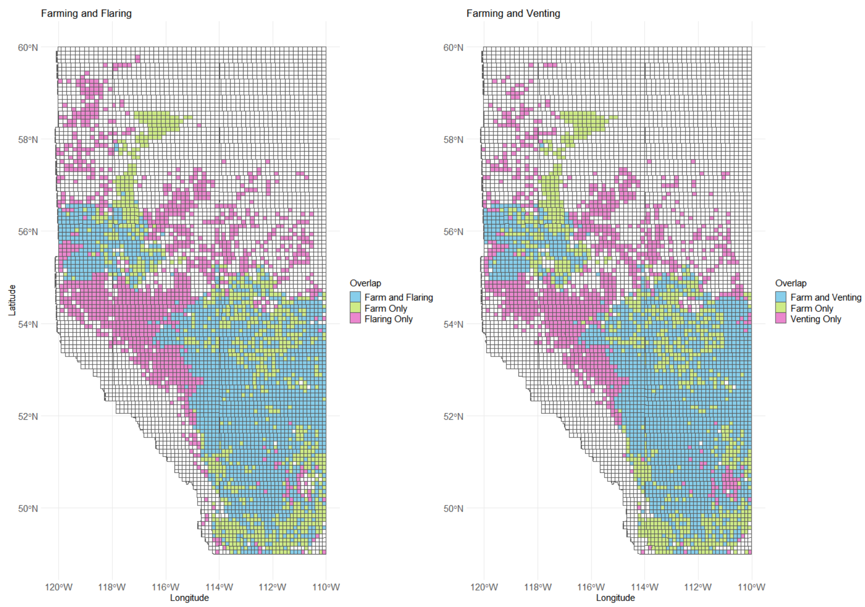



Figure B.2: Distribution of flaring and venting activity in Alberta, 2002-2019

Figure B.3: Overlap between Flaring, Venting and Farming by Township in Alberta, 2002-2019



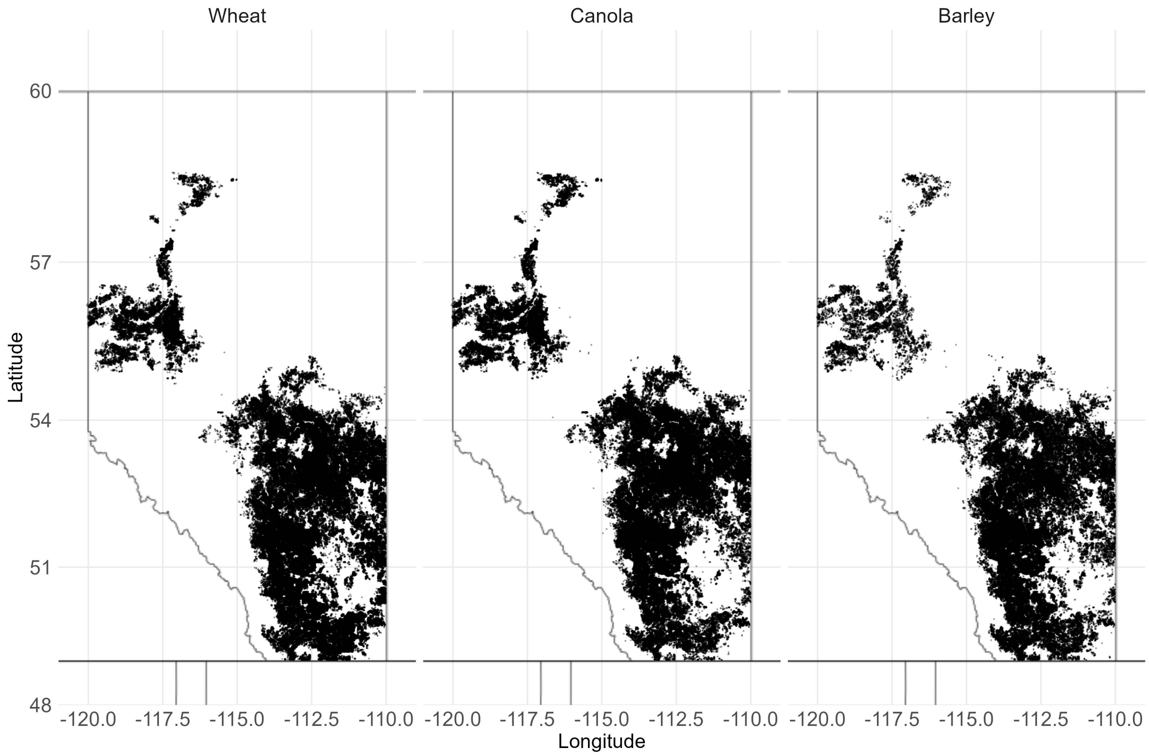

radii. As is evident, exposure is fairly constant once farms are within 20-30km of a flare stack or venting facility.

# C Identifying Sour Gas Wells

Sour wells were identified using the Sour Gas Well List and well license list, which indicates whether the well contains sour gas. These wells were linked to facilities using the Well to Facility Link file for Alberta. Since the link file is not exhaustive, facilities were also linked to wells where they were located in the same LSD. Additionally, sour gas processing plants were identified by facility ID using the ST50A file. The result is a binary variable indicating whether each facility has ever been linked to or co-located with a sour well, or is a sour gas processing plant. Though this measure is imperfect as it does not capture the difference in $H_2S$ concentration across sour gas wells, it can provide insight into whether sulphur deposition is a likely mechanism for the observed results.

Many oil wells in Alberta contain some $H_2S$, with about a third of natural gas production being classified as sour (Alberta Energy Regulator, n.d.). Based on the binary indicator constructed for sour gas, for the period 2002-2019 about

Figure B.4: Distribution of Acreage for Cash Crops in Alberta, 2002-2019



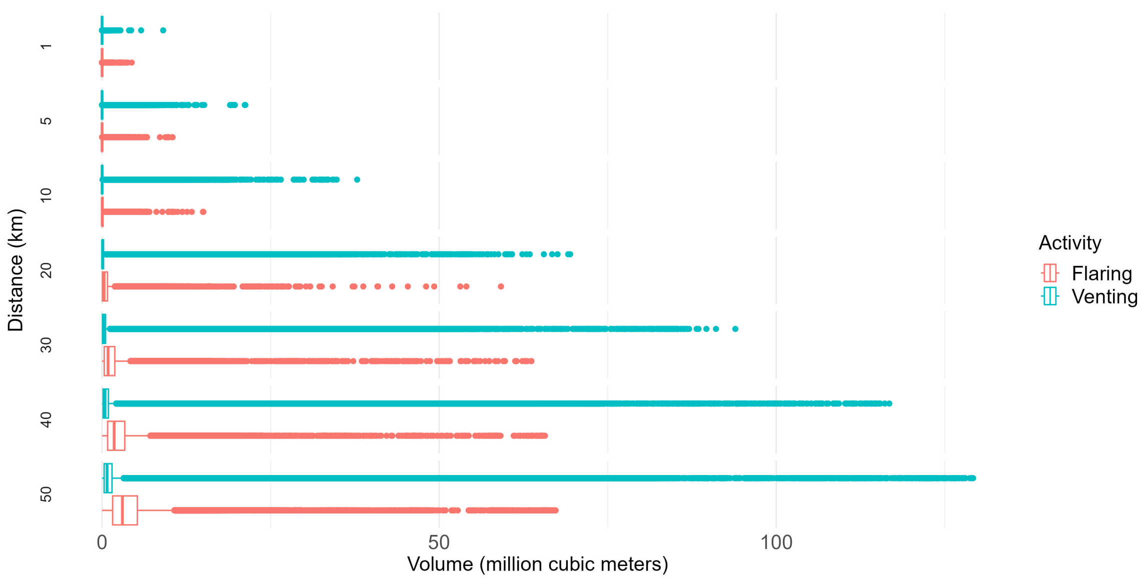




Figure B.5: Boxplots of flaring and venting exposure at varying distances, 2002-2019

70% of flared gas is sour, while only about 26% of vented gas is sour.

# D Additional Results and Robustness Checks: Short-Run

## D.1 Background on Plant Physiology

There is a long history of experimental work on the effects of air pollution on plants. We do not provide a comprehensive account of this work, but several useful reviews have previously been published on the topic (Heck, Dunning and Hindawi, 1965; Mudd and Kozlowski, 1975; Kulshrestha and Saxena, 2016). We provide a brief summary.

Many air pollutants are toxic to plants (i.e., phytotoxic), producing acute injury (i.e., cell death with visible damage), chronic injury (i.e., leaf yellowing or bleaching associated with destruction of chlorophyll), and hidden injury (i.e., damage that is not visible but affects plant physiology and growth) (Mudd and Kozlowski, 1975; Darrall, 1989; Kulshrestha and Saxena, 2016). Sulfur dioxide and nitrogen oxides can affect crops indirectly by contributing to acid rain, while nitrogen oxides and volatile organic compounds can affect crops indirectly as precursors to forming ground-level ozone, a well-known phytotoxin.

As described in the main text, the impact of sulfur dioxide, hydrogen sulfide, and nitrogen oxides on plants is non-linear. While higher concentrations decrease photosynthesis and can damage plant leaves, lower concentrations have been shown to increase rates of photosynthesis and plant growth. (Knabe, 1976; Darrall, 1989; Sabaratnam and Gupta, 1988; Hill and Bennett, 1970; Taylor and Eaton, 1966; Takahashi and Morikawa, 2014; Ausma and De Kok, 2019).

Ozone is particularly harmful to plants, affecting the ability of plants to photosynthesize and intake nutrients, with some studies suggesting it may be responsible for the majority of air pollution-related crop losses (Westenbarger and Frisvold, 1995). Recent modelling work suggests crop yield losses ranging from 3 to 16% globally due to the effect of ground-level ozone (Emberson, 2020). Other estimates are similar, with yield losses for soybeans, wheat, and maize ranging from 2.2 and 15% in 2000 (Avnery et al., 2011).

## D.2 Flaring and Air Pollution

Flaring and venting of solution gases result in the emission of greenhouse gases and air pollutants into the atmosphere. The emissions from venting are conceptually straightforward, since venting is a simple release of gases into the atmosphere. Solution gases are composed primarily of methane and, to a lesser extent, heavier hydrocarbons (e.g., ethane, propane), nitrogen gas, and carbon dioxide, as well as hydrogen sulfide when the gas is 'sour gas' (Johnson and Coderre, 2012). Solution gases can vary substantially in their composition both across reservoirs and wells, and because of limited data availability for solution gas compositions the specific emissions from venting at particular sites is more difficult to estimate (Johnson, Kostiuk and Spangelo, 2001; Johnson and Coderre, 2012).

Through combustion, flaring converts the hydrocarbons in the solution gas (e.g., methane) to carbon dioxide and, in the case of sour gas, the hydrogen sulfide into sulfur dioxide (Strosher, 2000). A host of other compounds are also emitted from flaring, for example volatile hydrocarbons (also known as volatile organic compounds), nitrogen oxides, and particulate matter such as black carbon (Strosher, 2000; McEwen and Johnson, 2012; Torres et al., 2012). Flares don't always burn at 100% efficiency, and incomplete combustion can result in some unburned solution gases being released and varying emissions of compounds such as nitrogen oxides and black carbon; the flare efficiency depends on factors such as flow rate, presence of liquid fuel, gas heating value, technology (e.g., steam or air assisted flares), and ambient conditions (importantly the presence of cross-winds) (Strosher, 2000; Leahey, Preston and Strosher, 2001). Estimates of combustion efficiency of flares vary considerably, ranging from as low as 62% (Strosher, 2000; Leahey, Preston and Strosher, 2001) to in excess of 98% (a level often used as the assumed rate), though the efficiency distribution is skewed (McDaniel and Tichenor, 1983; Gvakharia et al., 2017; Caulton et al., 2014).

## D.3 Additional Results and Robustness Checks

### D.3.1 Results for Equation 2

Table D.1 shows results from Equation 2, which estimates the semi-elasticity of agricultural land prices to municipal-level flaring and venting exposure. Three specifications are shown. The first specification omits all controls and fixed effects. The second specification adds in municipality and year fixed effects. The final specification includes flexible weather controls (the number of growing season hours within 1°C temperature bins and cumulative precipitation and polynomials in humidity) and municipality and year fixed effects.

Table D.1: Effect of Flaring and Venting on Land Prices

| | | | |
|---|---|---|---|
| Flaring volume (mcm) | -0.003 | 0.002 | 0.001 |
| | (0.001) | (0.001) | (0.001) |
| Venting volume (mcm) | -0.003 | -0.001 | 0.000 |
| | (0.001) | (0.001) | (0.001) |
| Controls | | | X |
| Municipality FEs | | X | X |
| Year FEs | | X | X |
| adj. $R^2$ | 0.010 | 0.867 | 0.873 |
| Obs. | 1202 | 1201 | 1201 |

Table shows regressions of land prices on flaring and venting exposure using municipality-level data. The dependent variable is the natural log of municipal land prices (per acre). The exposure variables are measured as volumes emitted within 50km of farms located within a municipality. The first column contains no controls or fixed effects. The second column adds municipality and year fixed effects. The third column adds both fixed effects and flexible weather controls including the number of growing season hours within 1°C temperature bins and cumulative precipitation and polynomials in humidity. Standard errors are clustered on individual municipalities.

### D.3.2 Robustness Checks

Table D.2 shows estimates of the short-run yield effect of flaring and venting from three alternative specifications. The first column estimates 1 without any controls or fixed effects. The second column adds weather controls to this specification. The final column adds both weather controls and fixed effects. Panel A shows estimates for barley yields. Panel B shows estimates for canola yields. Panel C shows estimates for wheat yields. The dependent variable in each specification is the natural log of per acre yields.

| *Panel A: Barley Yields (kg/acre)* | | | | | | |
|---|---|---|---|---|---|---|
| | No Controls | | Weather Controls | | Weather + F.E. | |
| | Est. | S.E. | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.006 | 0.000 | −0.002 | 0.000 | −0.005 | 0.001 |
| Flaring (mcm) | −0.005 | 0.001 | 0.000 | 0.001 | 0.007 | 0.001 |
| Obs. | 117 193 | | 117 193 | | 117 193 | |

| *Panel B: Canola Yields (kg/acre)* | | | | | | |
|---|---|---|---|---|---|---|
| | No Controls | | Weather Controls | | Weather + F.E. | |
| | Est. | S.E. | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | 0.000 | 0.000 | −0.001 | 0.000 | −0.001 | 0.000 |
| Flaring (mcm) | −0.006 | 0.000 | 0.001 | 0.000 | 0.003 | 0.001 |
| Obs. | 130 421 | | 130 421 | | 130 421 | |

| *Panel C: Wheat Yields (kg/acre)* | | | | | | |
|---|---|---|---|---|---|---|
| | No Controls | | Weather Controls | | Weather + F.E. | |
| | Est. | S.E. | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.002 | 0.000 | −0.002 | 0.000 | −0.003 | 0.000 |
| Flaring (mcm) | 0.004 | 0.000 | 0.006 | 0.000 | 0.006 | 0.001 |
| Obs. | 138 982 | | 138 982 | | 138 982 | |

The dependent variable is logged kg per acre measured as volumes emitted within 50km of a farm with omitted 5km donut holes surrounding flaring and venting sites. Standard errors are clustered on individual farms.

Table D.2: Effect of Flaring and Venting on Agricultural Yields, Alternative Specifications

Table D.3 shows estimates of the short-run yield effect of flaring and venting for exposures within 50km. The first column estimates 1 with exposures based on all venting and flaring within 50km of each farm (i.e., the "No Donut" specification). The second column excludes venting and flaring within 5km of each farm (i.e., the “Donut” specification). Panel A shows estimates for barley yields. Panel B shows estimates for canola yields. Panel C shows estimates for wheat yields. The dependent variable in each specification is the natural log of per acre yields. The results are not sensitive to the donut specification.

| *Panel A: Barley Yields (kg/acre)* | | | | |
|---|---|---|---|---|
| | No Donut | | Donut | |
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.005 | 0.001 | −0.005 | 0.001 |
| Flaring (mcm) | 0.007 | 0.001 | 0.007 | 0.001 |
| Observations | 117 193 | | 117 193 | |
| *Panel B: Canola Yields (kg/acre)* | | | | |
| | No Donut | | Donut | |
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.001 | 0.000 | −0.001 | 0.000 |
| Flaring (mcm) | 0.004 | 0.001 | 0.004 | 0.001 |
| Observations | 130 421 | | 130 421 | |
| *Panel C: Wheat Yields (kg/acre)* | | | | |
| | No Donut | | Donut | |
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.003 | 0.000 | −0.003 | 0.000 |
| Flaring (mcm) | 0.006 | 0.001 | 0.006 | 0.001 |
| Observations | 138 982 | | 138 982 | |

The dependent variable is logged kg per acre measured as volumes emitted within 50km of a farm. All specifications include flexible weather controls and farm and year fixed effects. Standard errors are clustered on individual farms.

Table D.3: Effect of Flaring and Venting on Agricultural Yields, Donut Specification

Figures D.6 and D.7 shows estimates of the short-run yield effect of flaring and venting for exposures within varying distances. Equation 1 was estimated based on venting and flaring within 5km, 10km, 20km, 30km, 40km, and 50km of each farm (note that these are “No Donut” specifications). The dependent variable in each specification is the natural log of per acre yields. The results show that the estimates become more precise moving to a larger exposure radius. For venting, estimates are not significant at distances shorter than 20km, with canola results becoming significant only at distances of 40km and 50km. For flaring, estimates are significant at all distances, and show a trend to smaller coefficients and more precise estimates at larger distances. While we do not measure air pollutant concentrations at distances from the flare sites or at each farm, ambient concentration effects from point source emissions can be expected to decrease at greater distances from the source due to the dispersion of the plume over greater areas. Accordingly, while greater total volumes are included with a 10km radius than for a 5km one, these volumes are spread over a much larger area (consider that the area of (the sector of) a circle increase with the square of the radius). Further, the higher estimates from the 5km radius lend additional credibility to the donut specification, which excludes these volumes.

Figure D.6: Venting Results by Distance

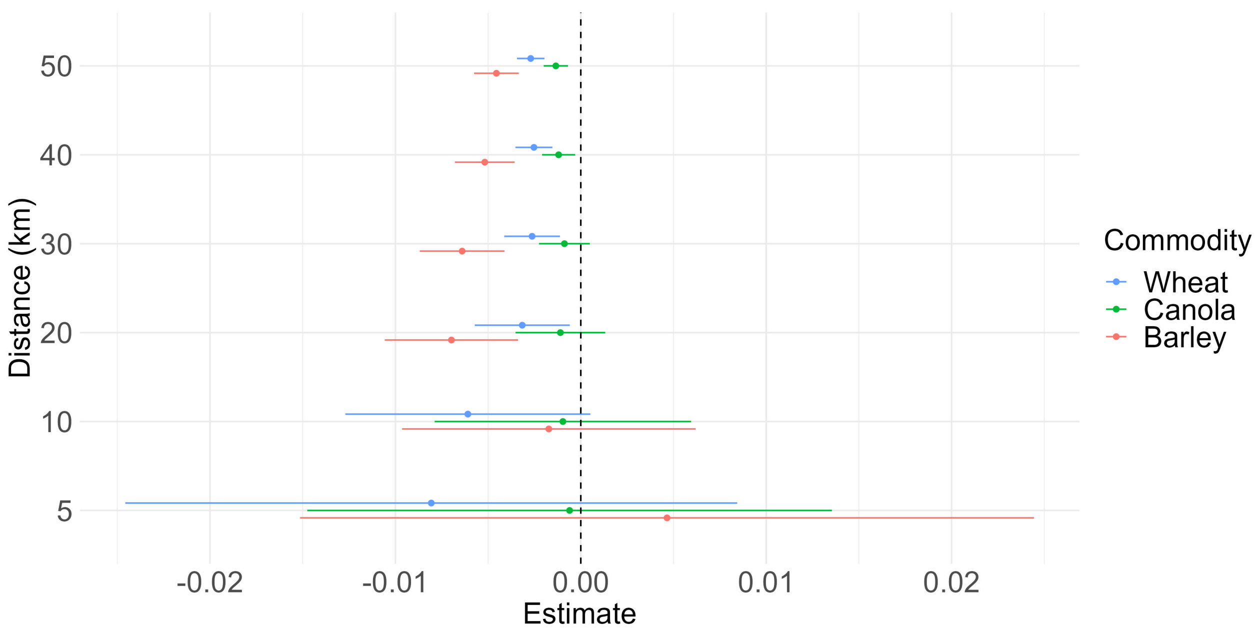
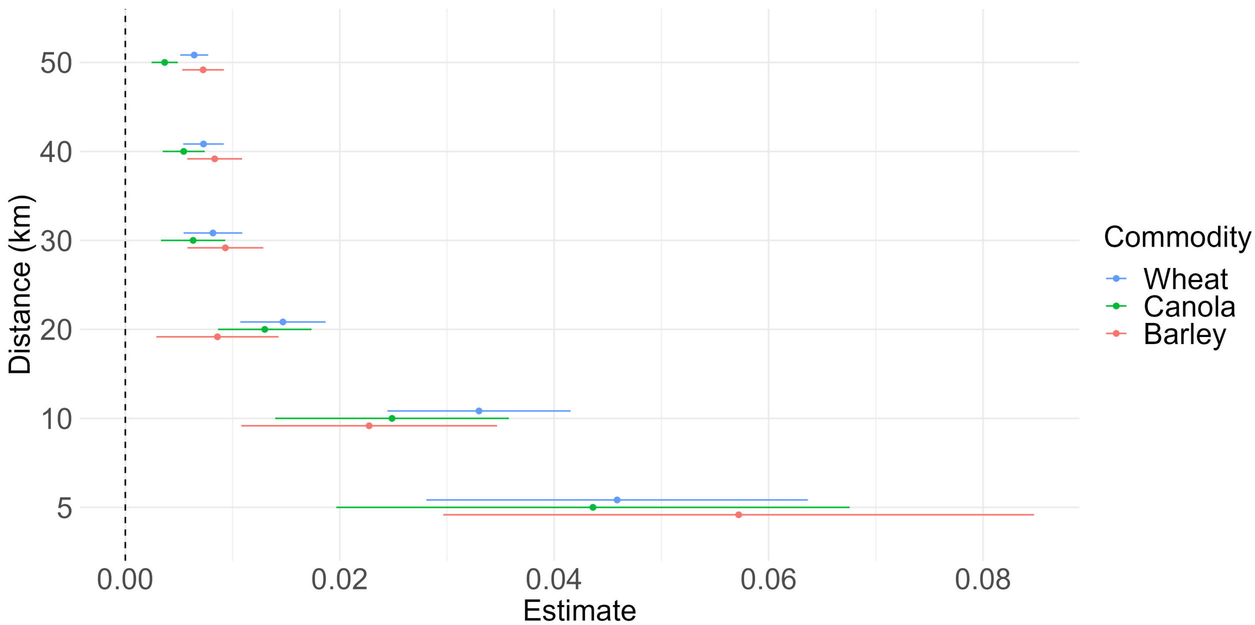



Table D.4 shows estimates of the short-run yield effect of flaring and venting for exposures controlling for nearby oil and gas production. Oil and gas

Figure D.7: Flaring Results by Distance




production were calculated as all production from crude oil and bitumen batteries within 50km of each farm. Data for oil and gas production come from the AER's ST60 report, which includes monthly oil and gas production at the facility level. The results show that including controls for nearby oil and gas production have negligible effects on the estimates of the effect of flaring and venting on yields.

*Panel A: Barley Yields (kg/acre)*

| | Main model | | Production Controls | |
|---|---|---|---|---|
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.005 | 0.001 | −0.005 | 0.001 |
| Flaring (mcm) | 0.007 | 0.001 | 0.006 | 0.001 |
| Oil Production (mcm) | | | 0.029 | 0.019 |
| Gas Production (bcm) | | | −0.027 | 0.009 |
| Observations | 117 193 | | 117 193 | |

*Panel B: Canola Yields (kg/acre)*

| | Main model | | Production Controls | |
|---|---|---|---|---|
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.001 | 0.000 | 0.000 | 0.000 |
| Flaring (mcm) | 0.003 | 0.001 | 0.004 | 0.001 |
| Oil Production (mcm) | | | −0.094 | 0.016 |
| Gas Production (bcm) | | | 0.015 | 0.008 |
| Observations | 130 421 | | 130 421 | |

*Panel C: Wheat Yields (kg/acre)*

| | Main model | | Production Controls | |
|---|---|---|---|---|
| | Est. | S.E. | Est. | S.E. |
| Venting (mcm) | −0.003 | 0.000 | −0.004 | 0.000 |
| Flaring (mcm) | 0.006 | 0.001 | 0.006 | 0.001 |
| Oil Production (mcm) | | | 0.061 | 0.019 |
| Gas Production (bcm) | | | −0.031 | 0.006 |
| Observations | 138 982 | | 138 982 | |

The dependent variable is logged kg per acre measured as volumes emitted within 50km of a farm. All specifications include flexible weather controls and farm and year fixed effects. Standard errors are clustered on individual farms.

Table D.4: Effect of Flaring and Venting on Agricultural Yields, Oil and Gas Production

# E Conceptual Model: Farmer's Investment Decision

Policy interactions arise via taxes and investment in our setting. Investment involves a dynamic process, governed by a law of motion. To capture tax-investment dynamics and guide our empirical analysis, we develop a benchmark model of acreage dynamics. The model is kept as simple as is reasonable. We set output and investment prices to one, assume depreciation is zero[41] and suppress other short-run inputs such as labor and fertilizer (i.e., we assume a value-added specficiation where farmers have already optimized over these factors). None of the results depends on these assumptions.

Flow gross-of-tax net profits are:

$$\begin{aligned} \pi_t(A, \theta) &= F(A_t, \theta_t) - rA_t \\ &= A_t^{\beta}\theta_t - rA_t \end{aligned} \tag{6}$$

where for expositional ease a specific functional form is assumed for the production function in the second line. In (6), $\beta$ is a coefficient representing returns to scale, $\theta_t$ is expected period $t$ productivity which, when realized, is denoted $\tilde{\theta}_t$, and $r$ is the exogenous rental price of an acre. We work in discrete time, so $t$ refers to a specific period. Investment, $I_{t+1}$, follows a law of motion:

$$I_{t+1} = A_{t+1} - A_t. \tag{7}$$

As described in the main text, the interaction of positive productivity shocks with section 30 leads farmers to deviate from the optimal farm size. This is because there is a mismatch between when taxes are booked and when the effect of investments are realized. Positive income surprises in period $t$ (e.g., due to a productivity bump from flaring) lead to an effective investment subsidy at the start of period $t+1$, *even if the farmer knows she is deviating from optimal farm size*. This feature of tax code timing is the cause of the intertemporal policy

[41]Assuming no depreciation on agricultural land is consistent with its tax treatment in Canada. Farming operations are allowed to expense farm improvement expenses in the same year that they are incurred but are not granted any capital cost allowance (i.e., deductions on depreciated land values) (Canada Revenue Agency, 2023). Farm land can, however, if not maintained (e.g., shrubs and weeds encroach into productive fields).

interaction. Deviations from optimal firm size are a cost to the farmer because excessive land lowers the expected return per acre.[42] It is therefore useful to define the deviation variable (Caballero and Engel, 1999):

$$z_{t+1} \equiv \frac{A_{t+1}}{A^*}$$

which represents the how far farmers stray from optimal farm size. When acres, $A_{t+1}$, are chosen such that $z_{t+1} = 1$, the farm is at it's optimal size. Using $z_{t+1}$, it is possible to rewrite gross-of-tax flow profits as:

$$\pi_{t+1}(z) = \left( z_{t+1}^{\beta} \frac{r}{\beta} - r z_{t+1} \right) A^* \tag{8}$$

This is identical to (6) with a change of variables to represent the relevant farmer decision.

Next, we introduce taxes and write the net-of-tax decision problem in deviation form. Following a revenue surprise, farmers must pay extra taxes at the start of period $t+1$ equal to $\tau_t \cdot (A_t^{\beta} \tilde{\theta}_t - r A_t)$, where $\tau_t$ is the farmers effective tax rate in period $t$. This term is *subtracted* from gross-of-tax flow profits. Note that all variables in this tax payment term are indexed with $t$, but the decision is occurring in period $t+1$.

Section 30 allows this tax bill to be offset by investing in new land. Define $\tau_t' = \tau_t \mathbb{1}\{\tilde{\theta}_t > \theta_t\}$ . Section 30 acts like a subsidy for the farmer. Specifically, the farmer receives an effective investment subsidy worth $\tau_t' I_{t+1}$ for every dollar invested. This subsidy is *added* to the gross-of-tax flow profit equation. However, there are two limits on the investment rate. First, the investment subsidy cannot exceed the statutory tax burden. Second, there is a cost of investment that arises from deviating from optimal farm size.

Putting the pieces together and writing deviation form, in period, $t+1$, the farmer chooses $z$ to solve:

$$\pi_{t+1}(z) = \left( z_{t+1}^{\beta} \frac{r}{\beta} - r z_{t+1} \right) A^* - \tau_t' A^* \left( A^{*\beta-1} \tilde{\theta}_t + z_{t+1} + 1 \right) \tag{9}$$

[42] Alternatively, larger farms require a lower user cost of land because $\frac{dr}{dA}|_{A^*} < 0$.

giving the following first-order condition:

$$z^*_{t+1} = \left(\frac{r + \tau'_t}{r}\right)^{1-\beta} \tag{10}$$

The tax incentive, $\tau'_t$, arises from period $t$ returns but is realized in period $t+1$, hence causes an increase in $z_{t+1}$. Stated differently, the larger the incentive, the more the farmer is willing to increase $A_{t+1}$, deviating from optimal farm size, $A^*$. The essential feature of this first-order condition is that $t+1$ decisions depend on end-of-period taxes from the previous period, $t$. Whenever $\tau'_t > 0$, $\hat{z}_{t+1} > 1$ and the farm is larger than optimal. Taxes in the previous period lowers the price of investment in the current period. The rate at which farms expand is governed by the rate of decline in marginal productivity. The first-order condition demonstrates that returns fall until the value of the next acre equals the net of tax rental price of acres (or the tax benefit is exhausted). Eliminating section 30 is equivalent to setting $\tau'_t = 0$, thus removing the incentive caused by the policy interaction. When $\tau'_t = 0$, $\hat{z}_{t+1} = 1$ and the farmer chooses the optimal farm size.

# F Additional Results and Robustness Checks: Long-Run

## F.1 Cash Crops

Cash crops represent the majority of farm returns and acreage in Alberta. Farms' acreage can be split into two groups: total acreage in cash crops (i.e., barley, canola and wheat), those that account for the vast majority of farm activities , and total acreage in all other crops (e.g., peas, oats, legumes, among others). Cash crops represent roughly 86.1% of total acres in Alberta (Statistics Canada, 2023).

Mirroring the total acreage results, Figure F.8 and Table F.5 look at heterogeneity across cash and non-cash crops. Figure F.8 demonstrates that the acreage response is entirely driven by the major cash crops. Panel A shows the response for cash crops (i.e., barley, canola and wheat). Panel B shows other crops. The response to flaring is on the left, while the venting estimates are on the right-hand side.

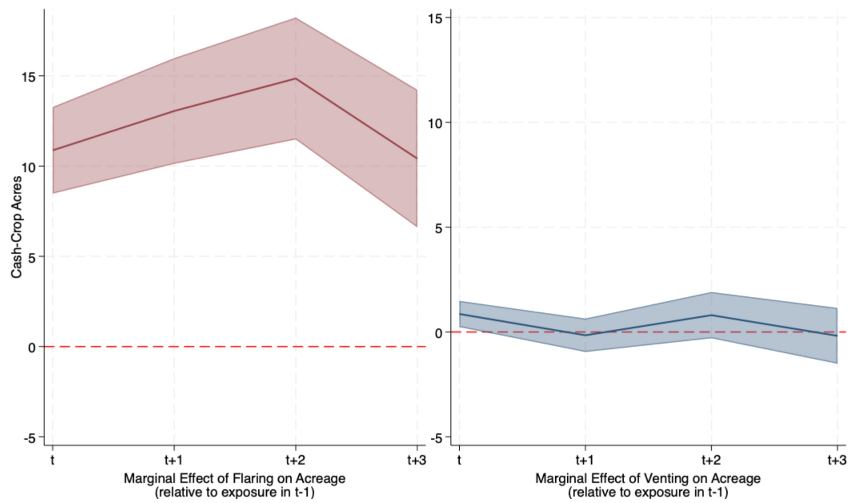
As with total acreage, a large and persistent response to flaring exposure is obvious for cash crops. Farms respond to an increase in flaring exposure by cultivating an additional 10.9 acres of cash crops per mcm of exposure, increasing to 13 acres in year 2, before leveling off at 14.6 acres within six years of exposure. Also, identical to the total acreage results, precise zeros are found for a negative shock due to exposure to venting. The venting results maintain for both cash and non-cash crops. There is no statistically detectable change in farm size arising from venting exposure.

Interestingly, differences emerge for the flaring response for non-cash crops. Commodities such as oats, rye and peas comprise less than 15% of the farmland in Alberta. As Figure F.8 and Panel B of Table F.5 demonstrate, there is no farm size response to temporary pollution shocks for these crops. Again, coefficients show reasonably precise zeros. Farmers' only margin of adjustment is to grow cash crop acreage following a positive yield shock.

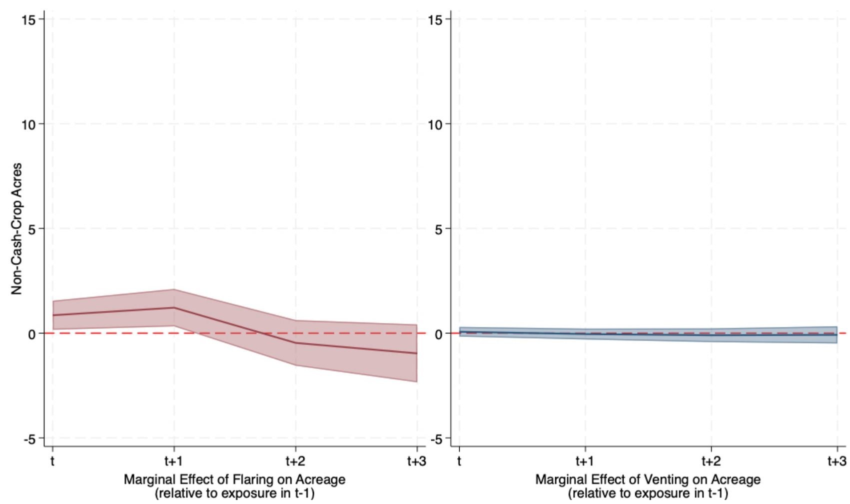
## F.2 Additional Tables and Figures on Mechanisms

Figure F.8: Investment Response to Flaring and Venting - Acres by Crop Type

(a) Cash Crops




(b) Other Crops



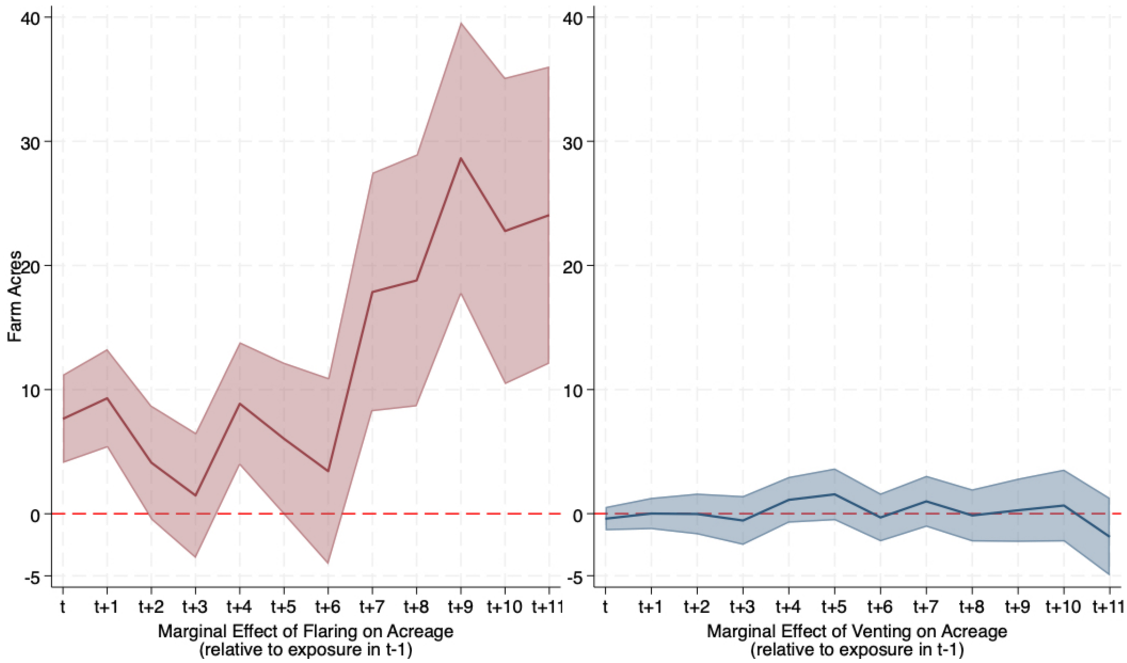

*Notes:* Figure shows point estimates and 95% confidence intervals for the local projection-dynamic panel analysis outlined in Equation 3. Panel (a) measures total acres planted in cash crops (i.e., barley, canola and wheat), while Panel (b) measures total acres planted in other crops. In each panel, the left inset shows the effect of flaring and the right inset the effect of venting. The dependent variable is the change in total acreage planted over the horizon relative to year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Acreage is winsorized at the 1% level.

Table F.5: Total Acres Planted as Cash Crops and Other Crops

| *Panel A: Cash Crops (Barley, Canola, and Wheat)* | | | | |
|---|---|---|---|---|
| | $\Delta$Acres | $\Delta^1$Acres | $\Delta^2$Acres | $\Delta^3$Acres |
| $\text{Flare}^{50}_{i,t-1}$ | $10.87^a$ | $13.05^a$ | $14.85^a$ | $10.42^a$ |
| | (1.22) | (1.49) | (1.72) | (1.95) |
| $\text{Vent}^{50}_{i,t-1}$ | $0.86^a$ | -0.16 | 0.80 | -0.18 |
| | (0.32) | (0.41) | (0.56) | (0.68) |
| $\text{Acres}_{i,t-1}$ | $-0.18^a$ | $-0.18^a$ | $-0.24^a$ | $-0.17^a$ |
| | (0.02) | (0.01) | (0.02) | (0.02) |
| *Panel B: Non-Cash Crops (e.g., Lentils, Oats, Rye, Peas)* | | | | |
| | $\Delta$Acres | $\Delta^1$Acres | $\Delta^2$Acres | $\Delta^3$Acres |
| $\text{Flare}^{50}_{i,t-1}$ | $0.85^b$ | $1.22^a$ | -0.46 | -0.97 |
| | (0.35) | (0.46) | (0.56) | (0.71) |
| $\text{Vent}^{50}_{i,t-1}$ | 0.07 | -0.04 | -0.10 | -0.08 |
| | (0.12) | (0.13) | (0.17) | (0.21) |
| $\text{Acres}_{i,t-1}$ | $-0.48^a$ | $-0.52^a$ | $-0.53^a$ | $-0.53^a$ |
| | (0.01) | (0.02) | (0.02) | (0.02) |
| Obs. | 184410 | 161990 | 141998 | 124106 |

*Notes*: Dependent variable is the change in total acres of cash crops in Panel A (barley, canola, and wheat) and other crops in Panel B planted over the horizon relative to year $t-1$, with horizons ranging from $t$ (column (1)) to $t+3$ (column (4)), respectively. Flare and vent treatment variables are defined at the 50km radius (less a 5km buffer around the farm) and are measured in the base year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level. Significance at the 1%, 5%, and 10% levels are denoted by $^a$, $^b$, and $^c$, respectively.

Figure F.9: Investment Response to Flaring and Venting, Long Horizon




*Notes:* Figure shows point estimates and 95% confidence intervals for the local projection analysis outlined in Equation 3, expanded to twelve periods. The left inset shows the effect of flaring and the right inset the effect of venting. The dependent variable is the change in total acreage planted over the horizon relative to year $t-1$. The sample is restricted to farms that operate throughout the entire 18-year sample. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level.

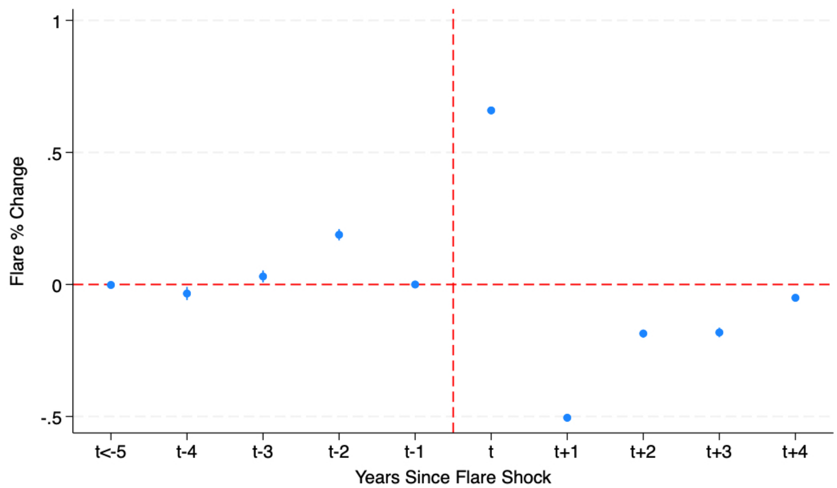
Table F.6: Yield Effects of Non-Routine Flaring and Venting Shocks

| | (1) Barley | (2) Canola | (3) Wheat | (4) Revenue |
|---|---|---|---|---|
| Flaring Shock (mcm) | -0.000 | $0.008^{a}$ | $0.016^{a}$ | $0.007^{a}$ |
| | (0.002) | (0.002) | (0.002) | (0.002) |
| Venting Shock (mcm) | $-0.017^{a}$ | $-0.011^{b}$ | $-0.026^{a}$ | $-0.023^{a}$ |
| | (0.005) | (0.005) | (0.005) | (0.004) |
| $N$ | 96382 | 105823 | 112800 | 163445 |

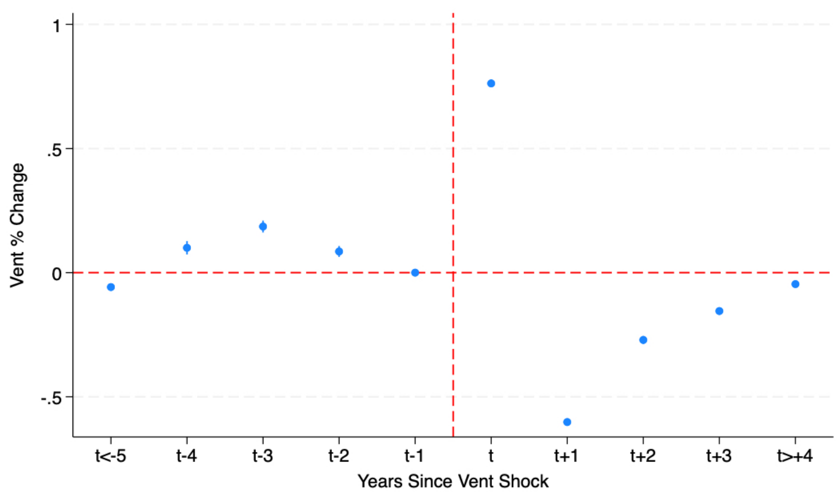
*Notes*: Dependent variable is the change in total acreage planted over the horizon relative to year $t-1$, with horizons ranging from $t$ (column (1)) to $t+3$ (column (4)), respectively. Flare and vent treatment variables are defined at the 50km radius (less a 5km buffer around the farm) and are measured in the base year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level. Significance at the 1%, 5%, and 10% levels are denoted by $^{a}$, $^{b}$, and $^{c}$, respectively.

Figure F.10: Non-Routine Flaring and Venting Event Study

(a) Flaring Shock




(b) Venting Shock




*Notes:* Figure shows point estimates and 95% confidence intervals for the non-routine flaring and venting shock.

Table F.7: Dynamic Investment Response to Non-Routine Flaring and Venting

| | (1) $\Delta$Acres | (2) $\Delta^1$Acres | (3) $\Delta^2$Acres | (4) $\Delta^3$Acres |
|---|---|---|---|---|
| Flaring Shock (mcm) | $6.52^a$ | $6.32^a$ | -0.23 | $3.57^b$ |
| | (1.48) | (1.49) | (1.86) | (1.77) |
| Venting Shock (mcm) | 6.66 | -5.47 | -2.71 | 5.04 |
| | (4.18) | (4.43) | (5.45) | (6.30) |
| $N$ | 152433 | 128038 | 107972 | 91141 |

*Notes*: Dependent variable is the change in total acreage planted over the horizon relative to year $t-1$, with horizons ranging from $t$ (column (1)) to $t+3$ (column (4)), respectively. Flare and vent treatment variables are defined at the 50km radius (less a 5km buffer around the farm) and are measured in the base year $t-1$. All regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags. All regressions include linear controls for base-year month-by-month precipitation, quadratic growing season humidity, linear temperature bins, and farm and year fixed effects. Standard errors are clustered by farm. Farm acreage is winsorized at the 1% level. Significance at the 1%, 5%, and 10% levels are denoted by $^a$, $^b$, and $^c$, respectively.

| | Barley | | Canola | | Wheat | |
|---|---|---|---|---|---|---|
| | Est. | S.E. | Est. | S.E. | Est. | S.E. |
| Mean Effective Tax Rate (000s acres) | 26.1 | 132.5 | 689.5 | 209.4 | 10.2 | 17.3 |
| Province FEs | X | | X | | X | |
| Year FEs | X | | X | | X | |
| Observations | 254 | | 179 | | 254 | |

Table F.8: Effect of Mean Effective Tax Rates on Seeded Acres, Provincial Level Data (000s acres)