

Hysteresis and the Environment: The Effect of Flaring and Venting on Agriculture*

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EARLY DRAFT. COMMENTS AND SUGGESTIONS WELCOME.

Abstract

Changes in environmental conditions prompt costly investments. Yet, the dynamics and persistence of these investments are often overlooked. We use confidential crop insurance data to study the dynamic investment responses of farms to environmental shocks induced by oil and gas operations in Alberta, Canada. We find that flaring and venting of “associated gases” from oil reservoirs alter the productivity of crop production. Affected farmers respond to these transitory shocks by permanently altering the size of their operations. Our results show that, through investment hysteresis, environmental shocks may affect allocative efficiency well after the shocks have abated.

1 Introduction

Changes in environmental conditions prompt households and firms to make costly investments. Some investments attempt to adapt to new conditions, such as the adoption of air conditioners during heat waves (Pavanello et al., 2021) or the installation of air filtration systems in response to air pollution (Ito and

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Zhang, 2020). Others serve to replace damaged capital following incidents such as natural disasters or wildfires (Pelli et al., 2023; Wang et al., 2021). These investments frequently yield persistent effects. New air conditioners change how interior temperatures are managed throughout the year and post-disaster capital upgrades support improved firm productivity. Yet, the dynamics of environmentally induced investments, beyond adaptation or replacement motives, have received little attention. This is despite the fact that they often reflect long-lasting changes in allocative efficiency induced by new environmental conditions. Ignoring these dynamics may lead to inaccurate assessment of the economic value associated with an environmental event, particularly if it is transitory in nature.

We study how changes in the environment affect the investment dynamics of firms. We uncover convincing evidence of hysteresis: Investment responses exhibit economically meaningful persistence even after environmental changes have abated. Specifically, we use confidential data on agricultural operations combined with spatially explicit environmental shocks linked to oil and gas development to demonstrate that farm operators make long-run agricultural investments in response to temporary changes in environmental conditions.

Hysteresis is familiar to economists (e.g., Yagan, 2019), yet research into environmentally-induced hysteresis is scant. More familiar is the concept of technological lock-in (Seto et al., 2016; Hawkins-Pierot and Wagner, 2023). Hysteresis and lock-in are complements. Both ideas focus on the dynamic causal effects of temporary shocks, or how initial regulatory and market conditions determine subsequent outcomes (Cullen and Mansur, 2017). Yet, while lock-in emphasizes the characteristics of particular technologies and production processes (e.g., putty-clay capital), hysteresis captures a wider array of phenomena. It encompasses how outcomes change through behavior, opportunity sets *or* technology, and includes describing the propagation path following an environmental shock. Importantly though, both hysteresis and lock-in manifest the long echo of short-run effects. These dynamic consequences can be critical for understanding responses to and the design of environmental regulation.¹

¹We emphasize that our data are stationary according to conventional tests. Unit root processes also display persistence as these series equal the sum of historical shocks (plus an initial value). Persistence in our context is not characterized by unit roots but by the lingering effect of a one-time shock.

Our backdrop focuses on the spillover from flaring and venting to agriculture. Flaring and venting are common in upstream oil and gas development.² Both are byproducts of crude oil extraction, caused by either a lack of infrastructure (i.e., insufficient project economics to collect, process and market the natural gas) or for safety (Alberta Energy Regulator, 2022b). In addition to emitting greenhouse gases, both flaring and venting also generate air pollution. Flaring generates carbon dioxide, nitrogen oxides, volatile organic compounds (VOCs), and sulphur dioxide (when the gas is sour); venting predominantly generates methane, heavier hydrocarbons, nitrogen, VOCs, and hydrogen sulphide (when sour) (Stroscher, 2000; Johnson, Kostiuk and Spangelo, 2001; Johnson and Coderre, 2012). In our setting – the Canadian province of Alberta – both activities are highly regulated. As such, our context provides plausibly exogenous variation in pollution exposure, where the degree of exposure and mix of pollutants to which a farm is exposed depends on its proximity to oil and gas activities, the sulphur content of those wells, and various macroeconomic conditions unrelated to the agricultural industry.³

To study the effects of flaring and venting on the agricultural industry, we combine confidential data from the public crop insurer and detailed regulatory information from the energy regulator in Alberta, Canada. We measure annual flaring and venting volumes at the facility-level for the near-universe of oil and gas facilities in the province, and then spatially link this to agricultural outcomes at the farm-field level. Using these data, the empirical analysis proceeds in two steps.

The analysis starts by testing whether crop yields physiologically respond to flaring and venting exposure in the short-run. These relationships are *a priori* unknown as the effects of air pollution on agricultural yields vary across pollutants. Using a fixed-effect estimation strategy paired with plausibly-exogenous

²Flaring refers to the combustion of “associated gases”, typically natural gas, trapped in oil reservoirs, while venting is the direct release of these gases into the atmosphere.

³The Alberta Energy Regulator, the agency that oversees the oil and gas industry, applies explicit rules as to when a well can flare or vent associated gases. These rules reflect resource characteristics such as the sulphur content at each well, the cost of capturing and transporting associated gases, and even an acceptable return on capital for the necessary infrastructure changes to capture associated gases. As such, changes in release volumes reflect variation in extraction volumes, proximity to pipeline infrastructure, pipeline capacity, the price of crude oil and natural gas, and changes in the regulatory directives governing flaring and venting.

changes in flaring and venting volumes and highly disaggregated data, we estimate the effects of exposure on yields of the three major crops in Alberta: barley, canola, and wheat. We find *increases* in yields in response to flaring for each crop of between 0.3% to 0.7% per million cubic meter (mcm) of exposure at affected farms, but *decreases* of between 0.1% to 0.5% per mcm of exposure in response to venting. These results mirror those of Metaxoglou and Smith (2020) and Sanders and Barreca (2022), who examine the effects of coal-fired electricity on crop yields.

Next, we turn to investment and hysteresis. We demonstrate that farmers internalize the short-run physiological response and adjust investment behavior by altering the size of their operations in the years following exposure. Investment, as we show, is inherently connected to asset values. Linking pollution to asset values has considerable intuitive appeal. The value of an agricultural parcel of land should represent its long-run productive capacity, which is a function of environmental quality. If farmers are forward-looking, their investment decisions should reflect expected changes in state variables (Severen, Costello and Deschenes, 2018; Bakkensen and Barrage, 2022). Initially, how farmers would respond to flaring and venting exposure is an open question, as it depends on the nature of expansion costs as well as the information farmers acquire from exposure (Hawkins-Pierot and Wagner, 2023). If expansion costs are asymmetric or non-convex, for example, farmers should respond to a permanent increase in productivity by expanding their farm’s footprint, but should not change their size in response to a negative shock.⁴ In contrast, a positive transitory shock should not lead to a permanent change in farm size, unless the farmer mistakes the transitory shock for a permanent one. If expansion is reversible and investment costs are convex, farm size may be more elastic to both positive and negative productivity shocks. Understanding whether flaring and venting induces an investment response among farmers is, therefore, important, as any response may engender long run effects from transitory pollution shocks.

The empirical challenge in studying investment responses lies in the dynamic nature of investment. We account for these dynamics by employing local projections (Jordà, 2005). Local projections predict farms’ investments over different time-horizons, relative to the pollution shock that occurs in a base period.

⁴This, of course, depends on the size of the productivity shock.

These projections can be conditioned on past investments, enabling us to estimate the long-run investment response to a transitory shock. Our investment response equation includes both farm fixed effects and a lagged dependent variable, however, 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, an innovation in the use of local projections.⁵

Our results suggest that farmers respond to the transitory flaring shock by permanently expanding the size of their farms, but do not respond to the negative venting shock. In the year following exposure, flaring leads farms to cultivate an additional 7.6 acres of land per mcm of exposure. This effect increases over time, reaching just over 14 acres within six years of exposure, representing a 1.5% increase in farm size for the average affected farm. Moreover, we are able to rule out increased asset values as an explanation for these expansions. Acreage expansion do not appear to have any effect on farm values. These patterns instead indicate that more complex dynamics are at play.

Uncovering these dynamics has noteworthy policy implications. We demonstrate that easily interpreted short-run effects may induce complicated long-run changes. Policies based on short-run results may therefore be poorly matched to longer-term policy objectives. Our results suggest this may be of particular concern in the case of pollution, which imposes acute effects but is often transitory. In our setting, at least, exposure creates persistent changes in economic behavior that would be hard to predict given observed short-run effects. Indeed, under-estimating the long-run response might lead decision-makers – and hence policy-makers – to under-price environmental quality.⁶ Over-estimating the response may encourage excessive averting behavior, harming citizens' well-being.⁷ Estimates for how long-run investment responds to environmental shocks are especially important when designing policy for climate change adaptation. Over-estimating positive short-run agricultural gains may, for example, lead

⁵To the best of our knowledge, a Blundell-Bond variant on a local projection has not been employed elsewhere. However, the idea was recently raised in Jordà (2023a).

⁶For example, if real estate transactions do not fully price in buyers' environmental valuations, policy-makers may obtain distorted willingness to pay estimates for environmental quality.

⁷Averting 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).

private agents to over-develop marginal lands even as yields are expected to decrease due to future nonlinearities in extreme heat (Schlenker and Roberts, 2009).

The paper closest to ours is Hawkins-Pierot and Wagner (2023). Hawkins-Pierot and Wagner find that energy prices in a manufacturing facility’s first year of operation dictate its future energy intensity. 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 current manufacturing energy intensity by 3%. Capital displays putty-clay characteristics and technology lock-in persists. Hawkins-Pierot and Wagner (2023) argue, as do we, the cause of lock-in is adjustment costs which limit firms’ abilities to re-optimize following a change in market or environmental conditions. In both their setting and ours, short-run conditions persist into the long-run. In their setting, the short-run condition in question is a market characteristic (i.e., energy prices). In contrast, we study short-run changes in environmental conditions.

Our results also contribute to two additional strands of literature. 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).⁸ 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 productive externalities can spill across economic sectors, leading to complex interactions that may be difficult to predict. Our paper is also among the first to demonstrate the consequences of venting, as venting data are rarely available.

Next, recent studies on air pollution’s effect on crop yields have offered conflicting results; 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. Their conclusions run in opposite directions. Metaxoglou and Smith (2020) demonstrate that nitrogen oxide emissions reduce

⁸Marks (2022) estimates that a modest tax on methane emissions from natural gas production would yield climate benefits on the order of \$1.8B. ADD RUDI K CITE.

yields, whereas Sanders and Barreca (2022) show that sulfur dioxide emissions improved yields.⁹ 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 6 concludes.

2 Data and Institutional Background

2.1 Flaring and Venting: Background, Regulation and Data

Petroleum reservoirs frequently have gases “in solution”. These gases must be managed to ensure safe operation of equipment. Associated gases in solution either sit above the crude oil or are dissolved into the resource. Absent collection infrastructure, or when project economics fail to justify building the network needed for onsite collection and downstream sale, these associated gases are either directly released into the atmosphere – vented – or burned in a flare stack – flared (Canadian Association of Petroleum Producers, 2022).¹⁰

Emissions from venting reflect the composition of the solution gas with the composition varying substantially across reservoirs. Methane is most prevalent, but other heavier hydrocarbons, such as ethane and propane, in addition to nitrogen, hydrogen sulfide and carbon dioxide are common (Johnson, Kostiuk

⁹Using 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.

¹⁰Venting was common early in the history of crude oil development. Health and safety concerns due to the flammability of these gases and frequent presence of toxic and odorous hydrogen sulfide resulted in a shift towards flaring.

and Spangelo, 2001; Johnson and Coderre, 2012).¹¹ Since methane is a potent greenhouse gas, converting it to carbon dioxide through flaring is the preferred method of disposal as carbon dioxide has a smaller global warming potential (assuming the gas cannot be collected and sold) (EPA, 2023). Combusting associated gases through flaring, however, can introduce additional challenges. Flaring causes a range of chemical reactions that, in themselves, produce a variety of air pollutants. Among others, pollutants from flaring include volatile organic compounds, nitrogen oxides, particulate matter and a range of carcinogenic compounds (Stroscher, 2000; McEwen and Johnson, 2012; Torres et al., 2012). Emissions also vary with flare efficiency, which depends on a variety of technical and environmental factors (Leahey, Preston and Stroscher, 2001; Gvakharia et al., 2017; Caulton et al., 2014).

If the associated gas contains hydrogen sulfide, it is referred to as ‘sour gas’. Flaring sour gas produces sulfur dioxide (Stroscher, 2000). That Alberta has a high prevalence of sour gas wells is important for this study. For the U.S., Sanders and Barreca (2022) demonstrate a positive relationship between sulfur dioxide and agricultural yields. This foreshadows one of our short-run results. We find differential effects when contrasting the effects of flaring and venting on agricultural yields, suggesting the same sulfur deposition channel as Sanders and Barreca (2022). (To continue the foreshadowing, we also find negative productivity effects for venting, mirroring the nitrogen oxide evidence of Metaxoglou and Smith (2020).)

Oil and gas operators in the province of Alberta are subject to a range of restrictions on flaring and venting activities. (Appendix A provides an overview of the province’s regulatory landscape.) For present purposes, we are interested in two rules, section 12.030(1) of the Oil and Gas Conservation Act and Directive 007. These regulations require all licensed oil and gas operators to publicly report volumes of solution gas produced, flared and vented on a monthly basis (Government of Alberta, 2022; Alberta Energy Regulator, 2021). These data cover more than 98% of all flaring and venting in the province.¹² Our analysis uses data for 2002 to 2019, encompassing 42,184 unique facility IDs, composed

¹¹Nitrogen oxides and volatile organic compounds are ozone precursors. They react in the presence of sunlight and heat to form ground-level ozone, a secondary air pollutant (Finlayson-Pitts and Pitts Jr, 1993; Krupa and Manning, 1988; Ainsworth et al., 2012).

¹²Only flaring and venting activity from confidential facilities are excluded.

of 464,613 flaring records across 21,593 unique facilities and 1,019,817 venting records across 31,276 unique facilities.¹³

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.¹⁴ Panel B shows that there is substantial volatility in flaring and venting volumes but that 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 reallocation of flaring and venting activity, with some regions seeing increased emissions, while others witnessed marked declines.) More stringent facility-level regulations, introduced in 2014, also prompted a decline in the number of facilities engaging in flaring and venting. An accompanying decrease in venting is consequently observable in the post-2014 period.

Facilities report flaring and venting data on a monthly basis and are uniquely identified in space to a legal subdivision (LSD). LSDs represent 400m x 400m grid tiles according to the Alberta Township System (ATS). Each LSD is defined by a centroid using ATS shapefiles.¹⁵ We then aggregate flaring and venting activity to the LSD-month level, resulting in 1,379,983 observations over the period 2002-2019.

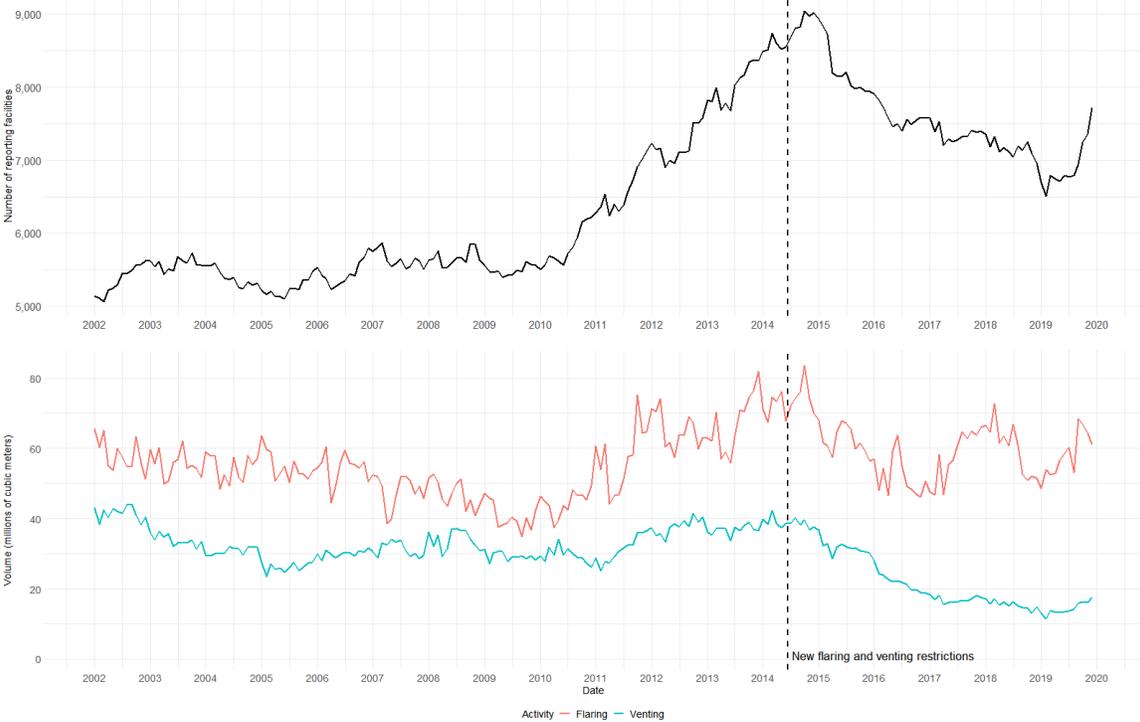
Figure 2 shows the spatial distribution of flaring and venting activity in Alberta for two distinct years, 2002 and 2019. Each point represents a facility. Red dots are for flare stacks. Blue dots are venting sites. The size of the “dot” reflects the volume of gas flared or vented. Fossil fuel development is clearly distributed according to the underlying resource; yet, also apparent is the variation in the type and location of the activity. Combining the time series and spatial

¹³In 2020, a handful regulatory definitions were changed, which limits the comparability of the pre- and post-2019 series.

¹⁴SAGD represents a method to extract bitumen without developing large surface mines.

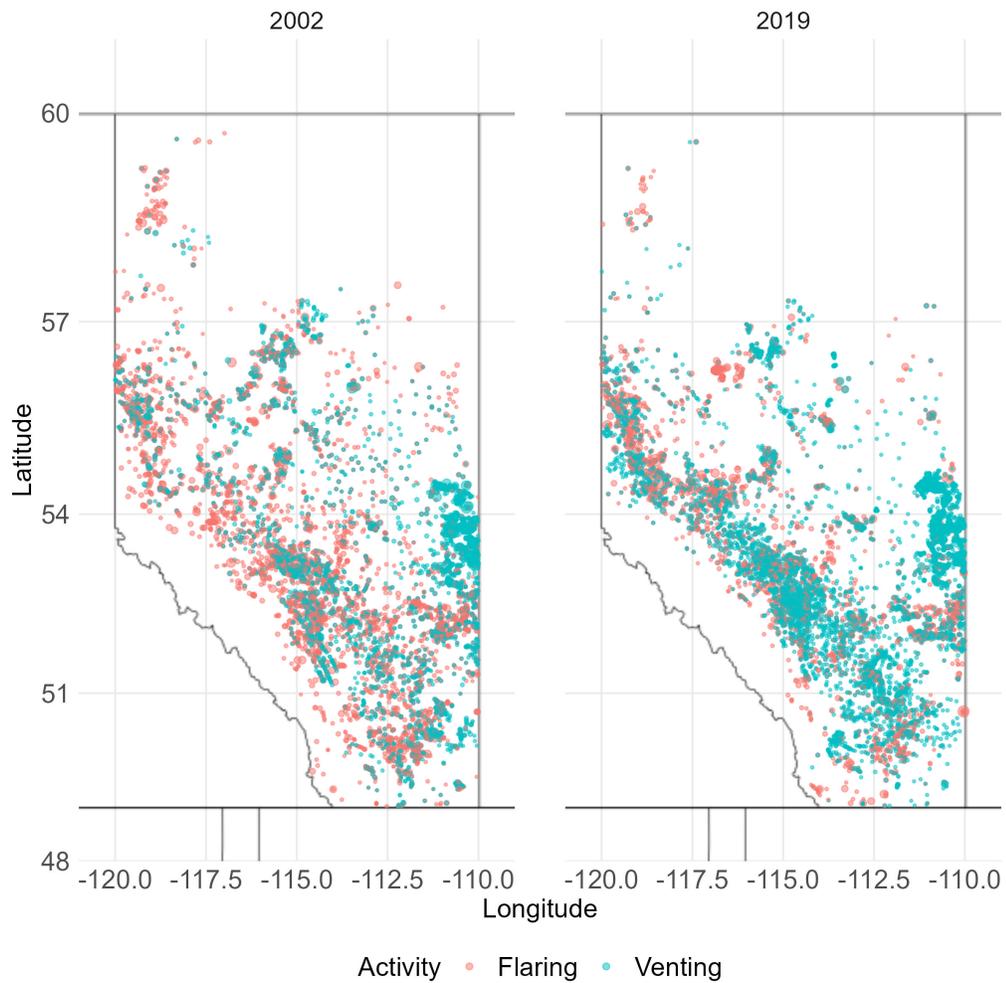
¹⁵These shapefiles delineate boundaries for the griddiles (e.g., townships, sections, quarter sections, and legal subdivisions) in the Alberta Township System.

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



variation enables us to pin down the short-run effects of flaring and venting on agricultural production. Subsequently, this joint spatial-temporal variation enables us to move to the farm-level and cross-sectionally isolate environmental shocks to productivity, which, when mapped to our agricultural data, allows us to demonstrate hysteresis.

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



2.2 Agricultural Yield and Acreage Data

Confidential data on farm-specific agricultural yields were provided by the Agriculture Financial Services Corporation (AFSC). AFSC is a provincially-owned enterprise (i.e., a crown corporation). It is the main provider of crop insurance and other financial services to farmers in Alberta.

Crop insurance contracts require farmers to report annual yield and acres planted data at the field level to AFSC. These yields and acre 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 the total acreage in Alberta.¹⁶ Each field in the data is associated with a set of coordinates that represent the field centroid. However, while the data are technically reported at the field-level, conversations with AFSC staff emphasized that there is actually less variation available. Many farmers report farm-by-commodity yields rather than field-by-commodity yields. Yields of, say, barley therefore represent the average across all barley fields within a farm rather than truly representing the yield per field output as reported in the datafile. We thus work with the slightly coarser annual farm-by-commodity data. The resulting farm-level dataset contains 394,950 observations over 2002 to 2019.¹⁷

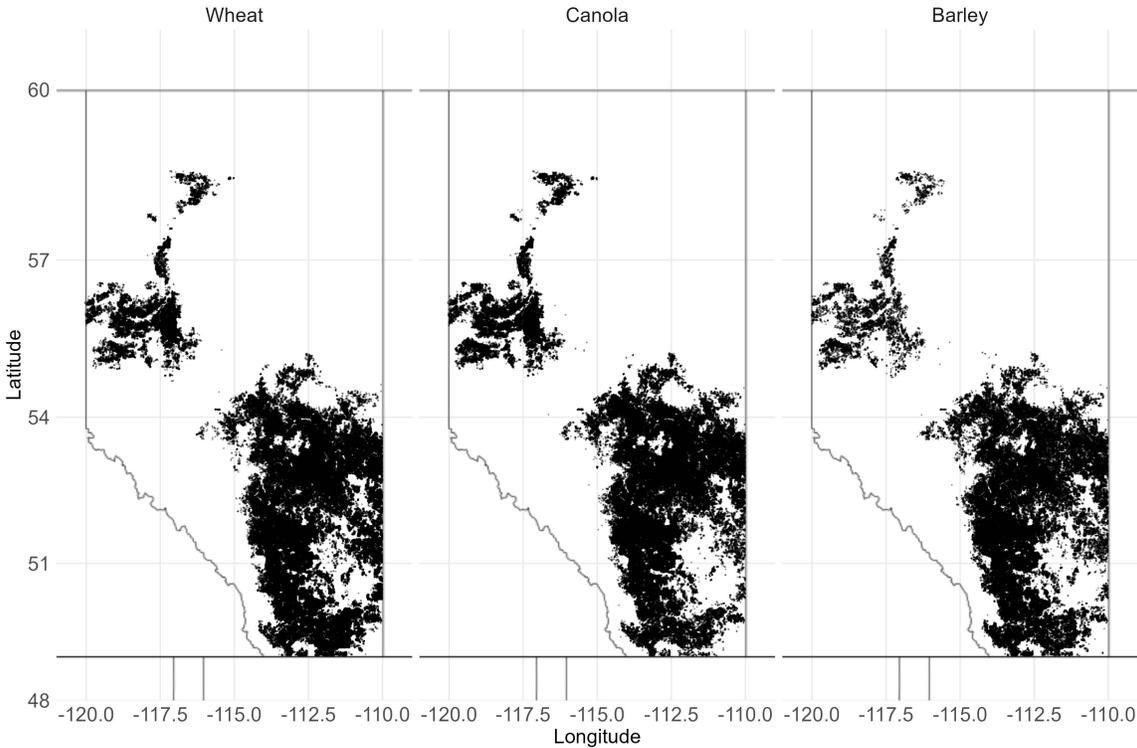
Figure 3 shows the distribution of total acreage for barley, canola and wheat for the period 2002 to 2019. Each point represents the acreage for a given field centroid over the period by crop type, with the size reflecting the relative acreage.

To illustrate the degree to which flaring and venting activity and agricultural fields are co-located, Figure 4 aggregates 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 town-

¹⁶Alberta accounts for 31.4% of Canada's total wheat production, 36.7% of canola and 47.7% of barley (Statistics Canada, 2023).

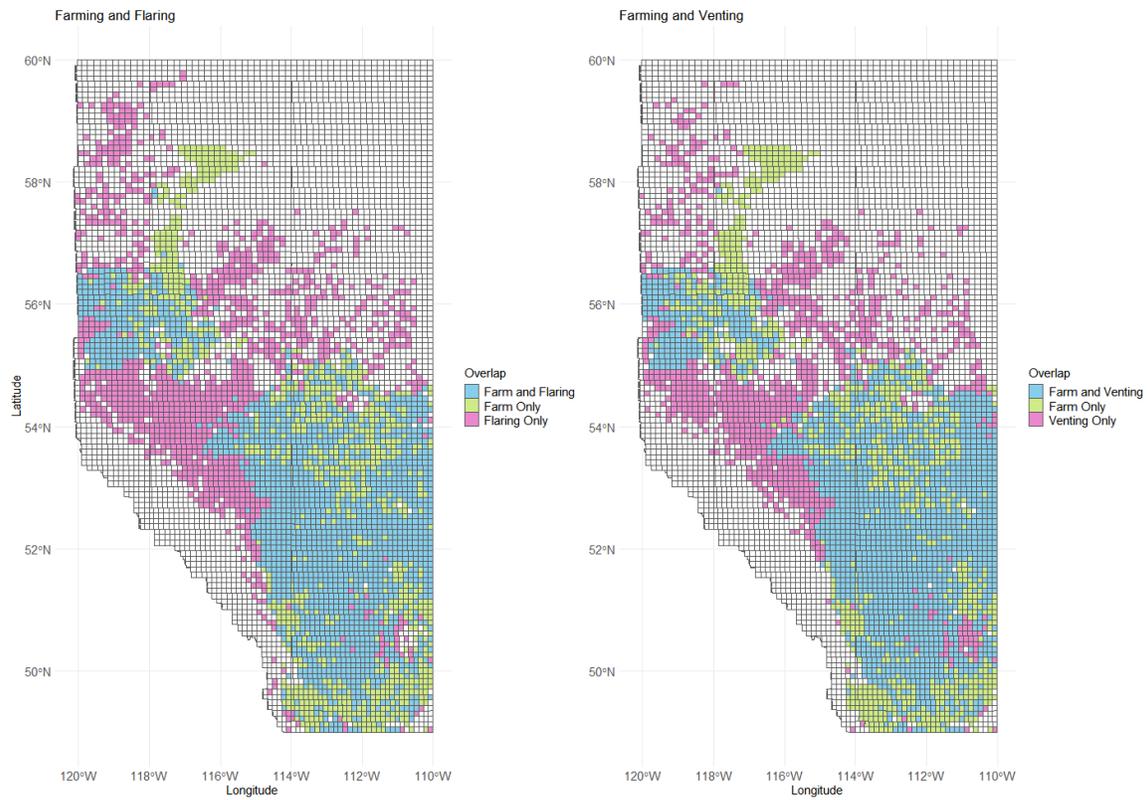
¹⁷We map each flaring and venting site, denoted by an LSD coordinate, to fields using fixed radii distances. Our preferred results start with a 50km, consistent with the specifications in Metaxoglou and Smith (2020) and Blundell and Kokoza (2022), then we exclude a 5km hole immediately around the fields. We retain only flaring and venting volumes emitted within a growing season, defined as April to August (Robertson et al., 2013). Figure B.3 in Appendix B shows farm exposure at 1, 5, 10, 20, 30, 40 and 50km radii, with the expected increase in exposure as surface area increases.

Figure 3: Distribution of Acreage for Cash Crops in Alberta, 2002-2019



ship can have a farm and no flaring activity; it may have flaring but no farming; or both flaring and farming may exist within the township. Similar coding is completed for venting.

Figure 4: Overlap between Flaring, Venting and Farming by Township in Alberta, 2002-2019



The left panel of Figure 4 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 4 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.2 in the Appendix contains additional information on the spatial distribution of exposure in annual volumes of flaring and venting across townships.

In addition to yield data, we also obtain field-level acreage data from AFSC.

Unlike yields, these acreages per crops are perceived as precise. Acreage is the variable upon which AFSC insures production. As such, they express high confidence in precise values of acres planted at the farm-level.

Weather Data

All models we estimate, both static and dynamics, contain extensive weather covariates. Weather is the critical time-varying input into agricultural output.¹⁸ 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 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. Flaring, venting, yields and acreage vary spatially in the cross-section and intertemporally within space. Because of the nature of yield reporting, we aggregate to the farm level by performing an acreage-weighted average for each field. We also trim the top and bottom 1% of the sample for yield by crop. After aggregating and trimming, we obtain 138,982 farm-by-year observations for

¹⁸Moreover, unlike, say, input prices for fertilizer, weather varies cross-sectionally within years.

wheat, 130,421 observations for canola and 117,193 observations for barley. We present summary statistics for the key variables in Table 1.

Table 1: Summary Statistics for Flaring, Venting and Agricultural Data

	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 620 acres with wheat, 543 acres with canola and 358 acres with barley. There is notable variation around these values as can be seen with the large standard deviations. This reflects 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 1,321 kg per acre, 814 kg per acre and 621 kg per acre.¹⁹ Flaring and venting are measured in million cubic metres or mcm. Farms experience average annual flaring exposure of between 3.8 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.

¹⁹We 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 22.8 bu per acre.

3 Physiology and the Short-Run Yield Response to Flaring and Venting

3.1 Set-up and Econometric Specification

There is compelling scientific basis to suspect that flaring and venting might impact agriculture. Pollutants associated with flaring and venting have been shown to be toxic to plants (Heck, Dunning and Hindawi, 1965; Mudd and Kozlowski, 1975; Kulshrestha and Saxena, 2016). The effects of sulfur dioxide, hydrogen sulfide and nitrogen oxide are non-linear, however. Higher concentrations decrease photosynthesis and damage plant leaves. Lower concentrations, on the other hand, have been shown to increase photosynthesis and improve 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).^{20,21}

We explore the physiological relationship between flaring and venting and agriculture by regressing yields on emissions volumes. For each major crop, wheat, canola and barley, we specify:²²

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

The dependent variable is Yield_{it} , per acre output from farm i in year t . We

²⁰Ozone is seen as particularly harmful to plants, affecting photosynthesis and nutrient intake. Several studies suggest that it may be responsible for the majority of air pollution-related crop losses (Westenbarger and Frisvold, 1995). Recent modelling show crop yield losses ranging from 3 to 16% globally due to the effect of ground-level ozone (Emberson, 2020) and yield losses for soybeans, wheat, and maize, specifically, ranging from 2.2 and 15% in 2000 (Avnery et al., 2011).

²¹Flares also emit significant 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, 2022a) 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 main specifications are “donut” specifications where we estimate the effect of flaring and venting on crop yields in a donut that excludes a hole around the field. Thus, the flaring and venting volumes around the immediate vicinity of the fields, where potential heat and light effects are more likely, are not included in the model.

²²Models are estimated separately for each crop as the physiological relationship between pollution and output may differ across crops.

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 then map flaring and venting volumes within a 50km radius of the farm (other radii are included in the Appendix as robustness). Next, we remove from this measure 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.²³

Our parameters of interest are β_1 and β_2 . β_1 captures the effect of an additional mcm of growing season flaring volumes emitted with 50km of farm i in year t on log yields. β_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, β_1 and β_2 , should be interpreted as reduced-form, intent-to-treat estimates. Our data allow us to exploit farm-level variation. However, pollution monitors are sparse in rural and agricultural areas of Alberta and direct measures of ambient pollution concentrations are unavailable. Further, even when the associated gases are identical, exposure to pollution may differ across operations. Inefficient combustion at one flare stack, for instance, may cause a farm to experience greater (or lesser) exposure to a specific chemical than an equally proximate farm near an efficient flare.

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 in-

²³To the extent that these factors remain, we estimate the joint effect of flaring and venting plus drilling.

cluded via 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 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, ρ_i and γ_t respectively. 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, ε_{it} is the error. Alberta closely monitors and regulates flaring and venting. Clear rules, reflecting the sulphur content, safety, the costs of capturing and transporting associated gases, and even an acceptable return on capital needed for infrastructure to support the processing of associated gases, characterize when a well is permitted to flare or vent. Given the combination of the regulatory environment, the geographical variation in production and infrastructure, temporal variation in oil and gas prices plus set-backs and the donut specification, we view farm decision-making as independent of variation in flaring and venting volumes. Robustness and placebo checks contained in Appendix C add credibility to this assumption.

3.2 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 per mcm of 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 with flaring by 0.3% per mcm, while wheat yields are 0.6% greater following exposure to flaring.

Most wells in Alberta are sour gas wells, with associated gases containing high proportions of hydrogen sulfide. Further, regulations in Alberta require that higher sulphur gas is flared (Alberta Energy Regulator, 2022a). Combustion of hydrogen sulfide during 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 this paper show that industrial pollution spillovers can prompt unexpected outcomes. Environmental regulation aimed at reducing acid rain and climate change may bring about negative short-run consequences for unrelated sectors.

The venting results contrast with the flaring estimates. Venting decreases agricultural yields. An increase in one mcm in venting volumes causes a -0.5% change in barley yields, -0.1% effect on canola yields and a reduction of 0.3% in wheat yields. Each of these effects is precisely estimated. The venting results further corroborate the sulfur deposition mechanism. The failure to convert hydrogen sulfide to sulfur dioxide means that the fertilization effect is absent, while the toxicity effect remains. We therefore expect and observe a decrease in agricultural yields from venting activities.

Our main conclusion from this initial analysis is that in the short-run, flaring in Alberta causes agricultural yields to increase, while venting causes them to decrease. We next explore whether these temporary pollution shocks, working through a physiological mechanism, bring about longer-term economic consequences. If our analysis stopped here, the conclusion would be that flaring

had a positive effect on agriculture, even if temporary. The reality, as we turn to next, is more complicated. Working through a farm size (i.e., investment) channel, we trace out asymmetric hysteresis as a response to the short-run productivity shocks.

Table 2: Effect of Flaring and Venting on Agricultural Yields, Donut Specifications

	Barley	Canola	Wheat
Flaring volume (mcm)	0.007 (0.001)	0.003 (0.001)	0.006 (0.001)
Venting volume (mcm)	-0.005 (0.001)	-0.001 (0.000)	-0.003 (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 with omitted 5km donut holes surrounding flaring and venting sites.

4 Investment and the Long-Run Acreage Response to Flaring and Venting

Next, we turn to the main contribution of this research. Hysteresis encompasses both permanent and temporary effects associated with the shock (Yagan, 2019). We explore both by estimating the dynamic causal effects attributable to the short-run, physiological shocks. Understanding how temporary pollution shocks from flaring and venting propagate over multiple years to produce lasting effects poses several empirical challenges, however. To work through the prospective pitfalls, we start by presenting a conceptual framework. This framework mimics Hawkins-Pierot and Wagner (2023) and Johnston (2017), guides our empirical analysis and offers intuition into the essential elements of farm investment decisions. The benchmark model is also a touchstone to

interpret the empirical results. That it is costly to adjust durable inputs is a feature of this framework. We differ, though, from Hawkins-Pierot and Wagner (2023) and Johnston (2017) in that our objective is to remain empirically agnostic with respect to the structure of adjustment costs and the nature of internal propagation.

After introducing the conceptual set-up, we present our empirical framework. Our focus is the path of firm responses rather than the static misallocation of inputs (e.g., Johnston, 2017; Asker, Collard-Wexler and De Loecker, 2014). Hysteresis characterizes the empirical pattern we observe. To show hysteresis, however, takes three steps. First, we identify propagation of a shock on future investment, allowing for serial correlation in exposure. Second, we condition on future values of flaring and venting to study the dynamic consequences of a one-off shock (Jordà, 2023*b*). These loosely correspond to the permanent and temporary characteristics of hysteresis. The nature of the data's field-specific spatial and intertemporal variation enables us to specify a pair of local projections models, accounting for these dynamic elements. Flaring and venting represent a farm-specific idiosyncratic shock observable to us as analysts. Finally, we connect short-run physiological responses to investment decisions and asset values. Asset values, or wealth, are what farmers ultimately care about. The propagation path help us understand paths of adjustment. Asset values offer final economic outcomes. Using our benchmark model of investment, we describe two methods to study the effect of flaring and venting on farm value.

4.1 Conceptual Framework: Investment in Acreage

Investment, and thus asset valuation, involves a dynamic process, governed by a law of motion. To guide our subsequent empirical analysis and capture these dynamics, we develop a benchmark model of farm investment that characterizes acreage dynamics.²⁴

Our objective is to keep the benchmark model as simple as is reasonable. We

²⁴As stated, the in-text framework follows Hawkins-Pierot and Wagner (2023) and Johnston (2017). Other models can offer different insights, however. A simple alternative demonstrates the source of information that we econometrically exploit. Assume farmers use a two-stage decision process (Angeletos, Lorenzoni and Pavan, 2010). In stage one, a farmer receives two

set output and investment prices to one, assume that depreciation is zero²⁵ and suppress other short-run inputs such as labour and fertilizer (i.e., we assume value-added specification where farmers have already optimized over these factors). Net farm profits depend solely on acres planted. Farmers then maximize the value of their enterprises by solving an intertemporal profit maximization problem where they choose their level of investment.²⁶ Investment responds to productivity shocks from flaring and venting. Changing farm size incurs planning and expansion costs. These include expenditures from acquiring new land (i.e., buying or renting new farms) or outlays to improve out-of-production fields. Dynamics arise through the following equation of motion:

$$A_{t+1} = A_t + I_t.$$

Acres planted next period are given by A_{t+1} : these equal acres this period, A_t , plus any investments the farmer undertook during the year, I_t .

Assuming that investment incurs adjustment costs means that expectations about future productivity are relevant for today's investment decisions. Indeed,

signals:

$$\begin{aligned} x_i &= \theta + \varepsilon_i \\ y &= \theta + u \end{aligned}$$

x_i is idiosyncratic to the farm. It is composed of θ , a normally distributed random variable with mean μ and variance $\frac{1}{\pi_\theta}$, that reflects the fundamental productivity of the land. ε_i is a one-period, mean zero shock, unique to the farmer that has variance $\frac{1}{\pi_x}$. y is a signal that is common to all farms in a region. It is comprised of the random fundamental productivity plus a common shock u . u , which is mean zero with variance $\frac{1}{\pi_y}$, may, for instance, reflect the prevalence of pests within a season. Assume that θ , ε_i and u are all independent.

In the second stage, the farmer chooses to invest in land, a , to $\max \mathbb{E}[\theta]A - \frac{A^2}{2}$, giving the following first-order condition:

$$A = \mathbb{E}[\theta] = \underbrace{\delta_0}_{\text{Farm FE}} + \underbrace{\delta_x x}_{\text{Identifying Variation}} + \underbrace{\delta_y y}_{\text{Time FE}}$$

where $\delta_0 \equiv \frac{\pi_0}{\pi}$, $\delta_x \equiv \frac{\pi_x}{\pi}$, $\delta_y \equiv \frac{\pi_y}{\pi}$ and $\pi = \pi_0 + \pi_x + \pi_y$. Thus, identifying variation arises from the farm-specific shock, after controlling for the farm- and time-specific effects.

²⁵Assuming no depreciation of 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 granted no capital cost allowance (i.e., deductions on depreciated land values) (Canada Revenue Agency, 2023).

²⁶Formulating the model in terms of investment is equivalent to specifying in terms of acreage.

understanding adjustment costs is essential to evaluating policies such as subsidies or taxes (Cooper and Haltiwanger, 2006). As becomes apparent, adjustment costs should also induce a positive relationship between farm value and investment. We do not observe this correlation in our empirical analysis.

Let farm value, V , be the discounted sum of net profits less outlays allocated to investment. Including investment adjustment costs, this equals:

$$V = E_0 \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} \{F(A_t; \vartheta_t) - I_t - C(I_t)\}$$

where r is the one-period discount rate. Given our assumptions on output prices and other inputs, revenues (net of operating costs) are determined by a production function, $F(A_t, \vartheta_t)$, which depends on acres and productivity, ϑ_t . Pollution shocks influence farm asset values via this productivity term. The adjustment cost function is given by $C(I_t)$. Minimal structure is placed on the cost function at this point. We speculate that, as in Hawkins-Pierot and Wagner (2023), they are comprised of fixed and variable components. Yet, because we approximate dynamics using local projections, we obtain dynamics without pinning down specific features of $C(I_t)$.

With these building blocks, the equation of motion and farm value model, we specify the Lagrangian, where the farmer chooses investment to maximize expected farm value:

$$\mathcal{L} = \max_{\{I_{t=0}^{\infty}\}} E_0 \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} \{F(A_t; \vartheta_t) - I_t - C(I_t) + \lambda_t(A_t + I_t - A_{t+1})\} \quad (2)$$

where λ_t is the Lagrange multiplier on the equation of motion. This is our benchmark model.

The benchmark model, (2), is a conventional investment specification; yet, it offers several important insights. Before discussing these, a few omitted components warrant mention. First, we implicitly assume an initial condition, $A_0 > 0$, and a transversality condition, $\lim_{T \rightarrow \infty} (1+r)^{-T} \lambda_T A_T = 0$. These ensure that any solution is well-behaved. More interestingly, a set of other behaviours and constraints could be added to influence decision-making. For instance, farmers may face cash flow limitations, non-convex adjustment costs or irreversibility

constraints (e.g., $A_{t+1} \geq A_t$). Some of these omitted elements are innocuous; others may be economically substantive for this context. Our immediate focus is providing a guide for the empirical analysis. We defer discussion of investment dynamics for the moment (but do return to several below).

Solving (2) gives the following first-order conditions for investment and next period's acreage:

$$I_t : -C_I(I_t) - 1 + \lambda_t = 0 \quad (3)$$

$$A_{t+1} : -\lambda_t + E_t \left[\frac{1}{1+r} \{ F_A(A_{t+1}; \vartheta_{t+1}) + 1 + C_I(I_{t+1}) + \lambda_{t+1} \} \right] = 0 \quad (4)$$

Our econometric analysis uses empirical analogues to these two first-order conditions, so conveying the economic intuition for these equations is important. More directly, they show how physiology connects to asset values.

As a first step, rewrite the first-order condition for investment:

$$\underbrace{1 + C_I(I_t)}_{\text{Marginal Cost of Acreage}} = \underbrace{\lambda_t}_{\text{Marginal Benefit of Acreage}}$$

The left-hand side of this expression is the marginal cost of farm expansion. Each new acre has a direct cost, equal to one, plus an additional adjustment cost, represented by $C_I(I_t)$. On the optimal path, this equals the Lagrange multiplier on the equation of motion, λ_t . Dynamics enter through λ_t as the Lagrange multiplier represents the shadow value of additional land, the marginal benefit from additional acres (i.e., the marginal benefit of farm expansion). It is the term through which pollution shocks influence investment and asset values. To see this, rewrite (4):

$$\lambda_t = E_t \left[\frac{1}{1+r} \left\{ \underbrace{F_A(A_{t+1}; \vartheta_{t+1})}_{\text{Return to Additional Acres}} + \underbrace{1 + C_I(I_{t+1})}_{\text{Saved Adjustment Costs}} + \underbrace{\lambda_{t+1}}_{\text{Future Value of the Farm}} \right\} \right]$$

Period t shadow value, λ_t , is comprised of the discounted sum of three terms. First, there is the return to additional land next period. This is given by $F_A(A_{t+1}; \vartheta_{t+1})$. The index is important here. Benefits of acreage depend on productivity in period $t + 1$. Expectations about future productivity enter via ϑ_{t+1} . Next, adjusting land in t avoids potential adjustment costs in $t + 1$. These saved costs are

captured by $1 + C_I(I_{t+1})$. Finally, the current shadow value of additional land depends on the ability to sell the farm next period, which is reflected in the future shadow price, λ_{t+1} .

Further intuition is found by iterating forward to eliminate λ_{t+1} . This gives the net present value of all future marginal returns and saved adjustment costs from investing in additional acres in period t . That is, it provides a marginal asset valuation equation:

$$\lambda_t = E_t \underbrace{\sum_{t=1}^{\infty} \frac{1}{(1+r)^t} \left\{ F_A(A_t; \vartheta_t) + (1 + C_I(I_t)) \right\}}_{\text{Marginal Value of an Additional Acre}} \quad (5)$$

All information about the future value of the firm is contained in (5). λ_t is a sufficient statistic for firm investment, clearly showing the channel through which pollution influences asset values and long-run decision-making – i.e., via the marginal productivity of land, $F_A(A_t, \vartheta_t)$. The benchmark model, therefore, enables us to characterize how investment and farm values respond to temporary pollution exposure, linking physiology to asset values.

Motivated by the first-order conditions, we proceed to the empirical analysis in two steps. First, investment is an implicit function of (3). Thus, we invert (3) to obtain a specification amenable to econometric estimation:

$$\begin{aligned} I_t = \Delta A_t &= C_I^{-1}(\lambda_t - 1) \\ &= \mathcal{M}(\lambda_t) \end{aligned} \quad (6)$$

Local projections are used to flexibly estimate this investment response as a function of pollution. Investment responds to changes in asset values, i.e., via the shadow value, λ_t and flaring and venting shocks incorporated in the ϑ_t term. Indeed, using (6), we can unpack propagation effects in multiple ways. Empirically, we focus on two. First, we identify the effect of a period t shock allowing for the possibility that exposure in t generates a positive probability of subsequent exposure in period $t+h$. That is, we do not sterilize the impulse response from the effect of subsequent shocks (Jordà, 2023b). This response path blends hysteresis with anticipation, however. As such, we also specify models where we condition on future exposure, mapping the dynamic causal effect of the period t

shock as a one-off exposure. This latter specification is in the spirit of Hawkins-Pierot and Wagner (2023). Both impulse responses, as well as the differences between them, offer insights into how pollution from the oil and gas industry influences the agricultural sector over time.

The response of investment to pollution is our main focus. Because we observe both positive and negative shocks, we are able to decompose dynamics along both the investment and disinvestment margins. However, (6) only characterizes one part of the link from physiology to asset values. In particular, investment offers one a method to describe dynamics following a shock. Tracing the investment path is inherently interesting and important for understanding adjustment path to interventions. Yet, investment dynamics may not fully characterize the final outcome of pollution for farmers. Farmers care about asset values, or wealth. To complete the conceptual framework, therefore, we develop an empirical analogue to (4) (akin to early work by Abel and Blanchard, 1986) to study asset values directly. Formulating this is more challenging than the investment model because at time t , acres are observable but the shadow price of land, λ_t , is not.

We tackle asset values two ways. First, we incorporate a supplementary dataset on agricultural real estate transfers in the province of Alberta. These data explicitly represents asset values. Using this real estate information, we specify classical hedonic models of farm value as a function of flaring and venting (Bajari et al., 2012; Currie et al., 2015). The advantage of these data are that they report the market value, acreage and count of agricultural lands transfers at the municipality-level in Alberta (Alberta, 2023). Agricultural land values reflect a bundle of attributes, including proximity to transportation, soil quality as well as exposure to pollution. Coefficients from hedonic models, thus, provide a method to capture the implicit marginal value of a change in flaring and venting volumes on real estate prices. Implicit prices are interpreted as the change in the value of the asset as a consequence of a change in the underlying characteristic (i.e., exposure to flaring and venting).

The upshot of the hedonic models is that, via implicit prices, they supply the direct effect of flaring and venting exposure on farm asset values. Unfortunately, two data challenges limit the analysis. First, Alberta's agricultural real estate transfer data is at the municipality-level, not the farm-level. There

are only 68 municipalities in the province, so this information is much coarser than the data used in the other analyses.²⁷ Second and more importantly, farm sales are rare. Only a limited number of farms are transacted each year and counts in a municipality-year cell may be sparse. Estimates from the hedonic regressions are, therefore, interpreted as the effect of flaring and venting on asset values, conditional on the subset of transfers that occurred within a period. Put differently, because only a handful of farms change hands in each year, we hesitate to draw strong conclusions about the population of crop enterprises in Alberta.

Due to these limitations, we also approach asset values from a separate direction. This alternative method leverages the investment results and continues to exploit the rich farm-level data. Our process is as follows. Agricultural land value, V_t , is the product of three terms: price per acre, the number of acres cultivated and the yield per acre. Land prices are market-wide and can be absorbed in a time fixed effect. Idiosyncratic variation in asset values are thus the product of the decision variable, acres, and yield per acre, the variable influenced by exposure to flaring and venting. Log-linearizing (cross-sectional) value around the steady state thus gives:

$$\% \Delta V = \% \Delta \text{Acres} + \% \Delta \text{Yield per Acre} \quad (7)$$

This expression says changes in farm value, $\% \Delta V$, can be decomposed into the growth in acres, $\% \Delta \text{Acres}$, plus the growth in yields per acre, $\% \Delta \text{Yield per Acre}$.

Linking physiology to asset values requires filling in these two pieces, terms that emerge organically from our benchmark model. First, our investment specification measures how farm size responds to flaring and venting, giving the change in acres, $\% \Delta \text{Acres}$. The missing piece is the change in yields due to farm expansion. This is straightforward to obtain from a regression of average farm-level yield on a lagged expansion term (plus fixed effects and controls). Because pollution exposure is temporary, estimating how yields respond to a lagged investment avoids many thorny issues with respect to expectations as long as we control for current productivity plus terms that capture previ-

²⁷Similarly, mapping of flaring and venting volumes to municipalities is also potentially more prone to measurement error. Appendix B describes how these data were collected and mapped to flaring and venting. It also includes a table of summary statistics.

ous pollution shocks. Last period’s investment acts as a sufficient statistic for the response of prior productivity, including the effect of flaring and venting. Thus, the coefficient on lagged change in acres in a farm-yield regression gives the second right-hand term, $\% \Delta \text{Yield per Acre}$. Combining the $\% \Delta \text{Acres}$ and $\% \Delta \text{Yield per Acre}$ estimates from the investment and farm yield regressions is the information needed to calculate the log-linear approximation for the change in asset values using the farm-level data.²⁸ Hence, (7) corroborates the hedonic regressions and offers a supplementary method to explore the effect of flaring and venting on asset values.

4.2 Investment Model: Econometric Set-up

Farm investment is dynamic with farm size as the stock variable. Shocks in at time t may persist, propagating over multiple periods. Conventional methods in environmental economics assess multi-period effects by estimating event study models or through adding model structure. Yet, 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 over time. We are interested in the *dynamic path* of the dependent variable. This is because it is precisely the dynamic nature of the stock variable, farm size, that encapsulates hysteresis and persistence. Capturing dynamic effects naturally suggests an impulse response function. We want to trace the time series path of our outcome variable following a shock. To estimate these propagation paths – and a farm’s investment response to flaring and venting exposure – 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 ex-

²⁸A simplified example helps clarify how (7) works. Assume that a temporary productivity shock leads to a farm-level investment response, generating a 0.6% increase in farm size. To bring these acres into production however, the farmer cultivates marginal lands, acres with a lower average yield. As a consequence, we expect a decline in overall yield per acre at the farm-level. Let the change in yield per acre due to farm expansion equal 0.4%. Combining terms, then, shows that the productivity shock caused farm value to increase by $0.2\% = 0.6\% + (-0.4\%)$. We claim, in this example, that asset values, *gross of adjustment costs*, increase as a consequence of the productivity shock.

tensively 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).

The appeal of local projections is parsimony and robustness to misspecification: it allows for time series dependencies in a particular dependent variable without fully specifying a multi-equation data generating process. The method allows the estimation of farms' dynamic investment responses to flaring and venting shocks, while flexibly controlling for the investment process. 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. Each offers a different perspective on hysteresis.

First we estimate the effect of exposure without conditioning on future values of flaring and venting. By omitting future values, we acknowledge that there is a positive probability that current period exposure is followed by additional exposure in subsequent periods (Jordà, 2023*b*). There are several advantages of this specification. First, it encapsulates potential adaptation that occurs over time, highlighting one of the ways that local projections differs from more conventional event studies. By excluding future exposure, we estimate the cumulative impact response caused by the shock. We do not sterilize the estimand of anticipation or expectations following the initial shock. Expectations are an important element of economic activity. Farmers may delay their response to the shock. We want to capture the impact over a series of periods. Next, our model includes an advantage unique to our setting. Both flaring, a positive shock, and venting, a negative shock, are included within the same model. This enables us to explore asymmetric propagation.

Define $t - 1$ as the base period. Thus, the model 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 $H = 5$, six years post exposure, or one-third of our panel length. Importantly, we also condition

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

on the farm’s size in year $t - 1$. As Jordà (2023b) describes, including a lagged dependent variable has two advantages. First, it acts as a sufficient statistic for previous interventions. In our setting, the 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, however. So, the Nickell bias is the cost of including lagged acres in our model (Nickell, 1981).³⁰ To circumvent this bias, we apply Blundell and Bond (1998) and estimate a system-GMM variant of each regression with the endogenous lagged variables are instrumented with deeper lags in both levels and differences, including lags of up to four periods as instruments.³¹

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

$$\begin{aligned} \Delta^h \text{Acres}_{it} = & \alpha_f^h \text{Flare}_{it-1}^{50km} + \alpha_v^h \text{Vent}_{it-1}^{50km} + \mu^h \text{Acres}_{it-1} \\ & + \mathbf{W}_{it-1}^{h'} \boldsymbol{\theta} + \rho_i + \gamma_t + e_{it+h} \quad h = 0, 1, 2, \dots, H, \end{aligned} \quad (8)$$

where the dependent variable, $\Delta^h \text{Acres}_{it} = \text{Acres}_{it+h} - \text{Acres}_{it-1}$, is investment by the farm, measured as the change in acres planted by farm i in year $t + h$ relative to the base period $t - 1$.³² In (8), $\text{Flare}_{it-1}^{50km}$ 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 Acres_{it-1} controls for the farm’s total acreage in the base period, which is the stock variable in Equation 5; ρ_i and γ_t are farm and year fixed effects, while \mathbf{W}_{it-1}^h is a vector of controls for weather conditions in the base period.³³

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

³¹Results are robust to adopting different lags as instruments.

³²Our 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.

³³These are identical to the controls in (1). They include monthly precipitation levels, a

The coefficients of interest are α_f^h and α_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. The parameters α_f^h and α_v^h capture the persistence and propagation of the farmers responses to that temporary shock as the change in farm size h years hence. α_f^h and α_v^h measure hysteresis.

Identification in (8) requires several conditions. Identical to section 3, 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. Year fixed effects control for common changes in fertilizer and output prices, while omitting the 5km donut holes ensures our exposure measures are not capturing other sources of local pollution. Expanding acreage is a costly investment. Farms only undertake this activity in response to changes in productivity or decreases in the cost of expansion. Thus, if changes in acreage over time are movements between steady states, the process also satisfies the stationarity assumption required of the Blundell-Bond estimator and local projections framework.

Next, we adopt a second approach to local projections where we do condition on future values of flaring and venting. This parallel model offers several additional insights. It acts as a robustness check on (8), by controlling for ongoing exposure to flaring and venting that occurs over the relevant horizon. Yet, it also gives a distinct estimand. By controlling for future exposure, we estimate the effect of a one-time treatment. That is, we trace the farm size propagation path for exposure in $t - 1$ exclusively. We do this for both flaring and venting.

quadratic in growing season humidity, and number of days per year that the maximum temperature hits a given level, in bins from zero to forty degrees Celsius.

This supplementary specification involves the following regression:

$$\begin{aligned} \Delta^h \text{Acres}_{it} = & \alpha_f^h \text{Flare}_{it-1}^{50} + \alpha_v^h \text{Vent}_{it-1}^{50} + \mu^h \text{Acres}_{it-1} + \mathbf{W}_{it-1}^{h'} \boldsymbol{\theta} + \sum_{j=0}^h \delta_f^j \Delta^j \text{Flare}_{it}^{50} \\ & + \sum_{j=0}^h \delta_v^j \Delta^j \text{Vent}_{it}^{50} + \rho_i + \gamma_t + e_{it+h} \quad h = 0, 1, 2, \dots, H, \end{aligned} \quad (9)$$

where $\Delta^j \text{Flare}_{it}^{50} = \text{Flare}_{it+j}^{50} - \text{Flare}_{it-1}^{50}$ and $\Delta^j \text{Vent}_{it}^{50} = \text{Vent}_{it+j}^{50} - \text{Vent}_{it-1}^{50}$ and all other variables are as defined in (8). The addition of $\Delta^j \text{Flare}_{it}^{50}$ and $\Delta^j \text{Vent}_{it}^{50}$ control for changes in the farm's exposure to both flaring and venting that occur during the horizon of interest, but after the base period. It is these additional controls that that change the nature of the estimand. As indicated by Equation 6, if farmers can predict future exposure based on current flaring and venting activities, then this should affect their investment response. Partialling out future changes in exposure isolates the one-period effect, which we then trace over time.

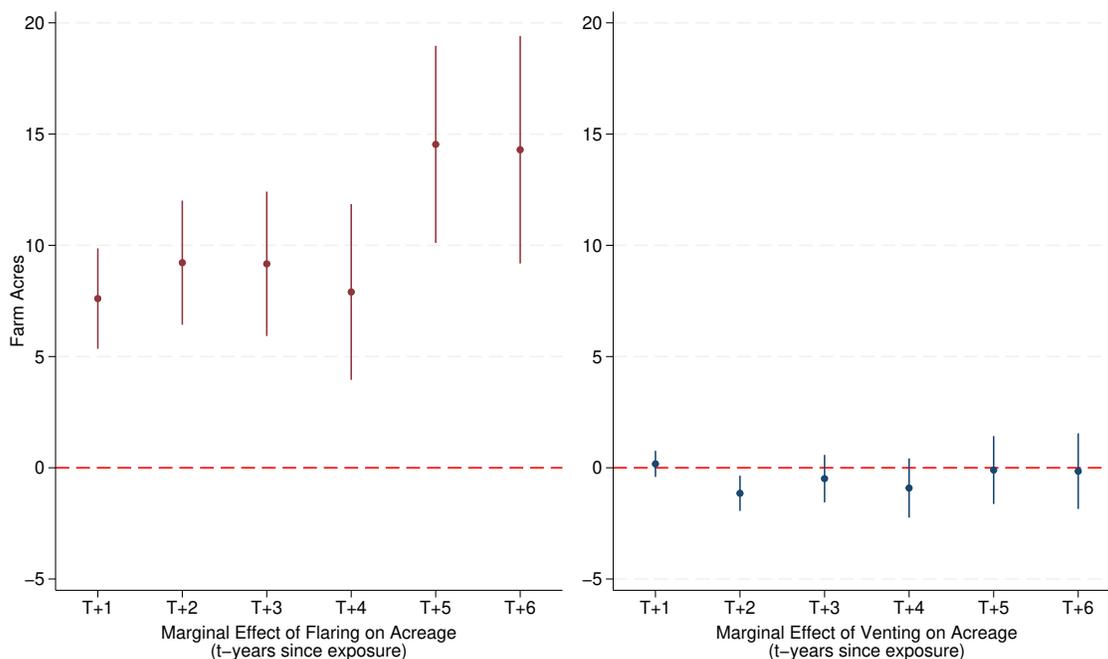
4.3 Investment Response to Flaring and Venting Exposure

Hysteresis refers to effects that persist after the causes that brought them about abate (Pindyck et al., 1991). Our results show that flaring creates hysteresis. Farmers respond to the temporary positive shocks created by flaring exposure. They permanently increase farm size. No response – and, therefore, no persistence – is found for the negative venting shocks.

The results from our first specification are presented in Figure 5 and Table 3. Exposure to flaring and venting occurs in period t . Figure 5 plots the coefficient estimates and 95% confidence intervals for flaring (left panel) and venting (right panel) exposure for each horizon, one year to six years after exposure. Table 3 reproduces these coefficient estimates as well as the coefficient estimates on lagged acreage. Results are for total acres planted. All regressions cluster standard errors by farm to account for serial correlation in farm investment.

For both flaring and venting, the results in Figure 5 and Table 3 are clear. There are persistent but asymmetric spillovers. Pollution from one sector, oil

Figure 5: Investment Response to Flaring and Venting - Total Acres Planted



Notes: Figure shows point estimates and 95% confidence intervals for the local projection-dynamic panel analysis outlined in Equation 8. 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.

and gas, works through a physiological mechanism, affecting the investment decisions in a separate sector, agriculture. Flaring causes hysteresis: temporary shocks to environmental conditions yield long-term changes in total farm acreage. There is no corresponding effect with venting exposure. That is, there is an asymmetric response to positive and negative shocks.

Farms exposed to flares cultivate an additional 7.6 acres of land per mcm of exposure in the year following exposure. The change in farm size is persistent, leveling off at just over 14 acres within six years. The average farm size in our sample is 1,039 acres. Exposure to a temporary flaring shock leads to an economically meaningful expansion of roughly 1.5% within six years versus a counterfactual scenario where the farm was not exposed to a flare. Pollution spillovers, as in Sanders and Barreca (2022), have positive effects for agriculture.

Table 3: Dynamic Investment Response to Flaring and Venting Exposure, Total Acres Planted

	(1)	(2)	(3)	(4)	(5)	(6)
	Δ Acres	Δ^1 Acres	Δ^2 Acres	Δ^3 Acres	Δ^4 Acres	Δ^5 Acres
Flare $_{i,t-1}^{50}$	7.61 ^a (1.15)	9.22 ^a (1.42)	9.17 ^a (1.66)	7.90 ^a (2.02)	14.54 ^a (2.26)	14.30 ^a (2.61)
Vent $_{i,t-1}^{50}$	0.18 (0.30)	-1.15 ^a (0.40)	-0.49 (0.54)	-0.91 (0.68)	-0.10 (0.78)	-0.15 (0.87)
Acres $_{i,t-1}$	-0.08 ^a (0.01)	-0.08 ^a (0.01)	-0.11 ^a (0.02)	-0.04 ^b (0.02)	-0.05 ^b (0.02)	-0.07 ^a (0.02)
<i>N</i>	184,410	161,990	141,998	124,106	108,131	93673

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 $t + 5$ (column (6)), 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.

The acreage response to venting is starkly different as is obvious in Figure 5 and Table 3. Indeed, Figure 5 and Table 3 show precisely estimated zeros. There is no investment response to venting. When oil and gas facilities release uncombusted associated gases, agriculture producers experience a negative yield shock. Yet, farmers do not disinvest or shrink their operations as a consequence of this negative shock. They maintain the steady state. It is also worth emphasizing that the flaring and venting paths are from the same set of regressions. So the contrast is 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. These patterns would be challenging to recognize with an event study framework. First, irreversibility appears to be a feature of farm expansion, and irreversibility causes hysteresis. Flaring and venting have opposite effects on yields. Yet, farm size weakly pushes in only one direction. Negative shocks have no effect. They do not induce smaller operations. Positive shocks encourage growth. Thus, pollution spillovers in this context encourage agricultural expansion. Interestingly, these micro-level results can be corroborated with aggregate evidence. Alberta, the province we study, the province with the sizable

majority of Canada's oil and gas development, is also the only major agricultural producing jurisdiction whose acres-planted increased over our period of study. Acreage in Alberta grew, despite the expansion of the oil industry, even as the number of acres in, say, Saskatchewan, Canada's bread basket, declined.

Asymmetry also suggests an unobserved constraint in farmer decision-making, one that is more nuanced. We speculate on this in the next section, but the conceptual framework hints at this. If it is costly to expand farm size, then farmers need resources to undertake these activities and cash constraints may affect investment. Negative shocks may pinch cash reserves, preventing desired expansions. However, since lagged acres are already cultivated, there is no incentive to shrink. Positive yields shocks, comparatively, provide the resources to pursue expansion.

Next, we extend these results. 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, those that account for the vast majority of farm activities (i.e., wheat, canola, and barley), 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 6 and Table 4 look at heterogeneity across cash and non-cash crops. Figure 6 demonstrates that the acreage response is entirely driven by the major cash crops. Panel A shows the response for cash crops, barley, canola and wheat. Panel B shows other crops. The response to flaring is on the left, while the venting estimates are on the righthand side.

As with total acreage, a large and persistent response to flaring exposure is obvious for cash crops, again suggesting hysteresis. 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 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 6 and Panel B of Table 4 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.

Table 4: Total Acres Planted as Cash Crops and Other Crops

<i>Panel A: Cash Crops (Barley, Canola and Wheat)</i>						
	Δ Acres	Δ^1 Acres	Δ^2 Acres	Δ^3 Acres	Δ^4 Acres	Δ^5 Acres
Flare ⁵⁰ _{<i>i,t-1</i>}	10.87 ^a (1.22)	13.05 ^a (1.49)	14.85 ^a (1.72)	10.42 ^a (1.95)	16.70 ^a (2.15)	14.63 ^a (2.40)
Vent ⁵⁰ _{<i>i,t-1</i>}	0.86 ^a (0.32)	-0.16 (0.41)	0.80 (0.56)	-0.18 (0.68)	0.59 (0.76)	-0.09 (0.82)
Acres _{<i>i,t-1</i>}	-0.18 ^a (0.02)	-0.18 ^a (0.01)	-0.24 ^a (0.02)	-0.17 ^a (0.02)	-0.18 ^a (0.02)	-0.18 ^a (0.02)
<i>Panel B: Non-Cash Crops (e.g., Lentils, Oats, Rye, Peas)</i>						
	Δ Acres	Δ^1 Acres	Δ^2 Acres	Δ^3 Acres	Δ^4 Acres	Δ^5 Acres
Flare ⁵⁰ _{<i>i,t-1</i>}	0.85 ^b (0.35)	1.22 ^a (0.46)	-0.46 (0.56)	-0.97 (0.71)	0.52 (0.71)	-0.65 (0.86)
Vent ⁵⁰ _{<i>i,t-1</i>}	0.07 (0.12)	-0.04 (0.13)	-0.10 (0.17)	-0.08 (0.21)	0.93 ^a (0.24)	0.41 ^c (0.23)
Acres _{<i>i,t-1</i>}	-0.48 ^a (0.01)	-0.52 ^a (0.02)	-0.53 ^a (0.02)	-0.53 ^a (0.02)	-0.60 ^a (0.03)	-0.68 ^a (0.03)
<i>N</i>	184,410	161,990	141,998	124,106	108,131	93,673

Notes: Dependent variable is the change in total acres of cash crops in Panel A (wheat, canola, and barley) and other crops in Panel B planted over the horizon relative to year $t - 1$, with horizons ranging from t (column (1)) to $t + 5$ (column (6)), 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.

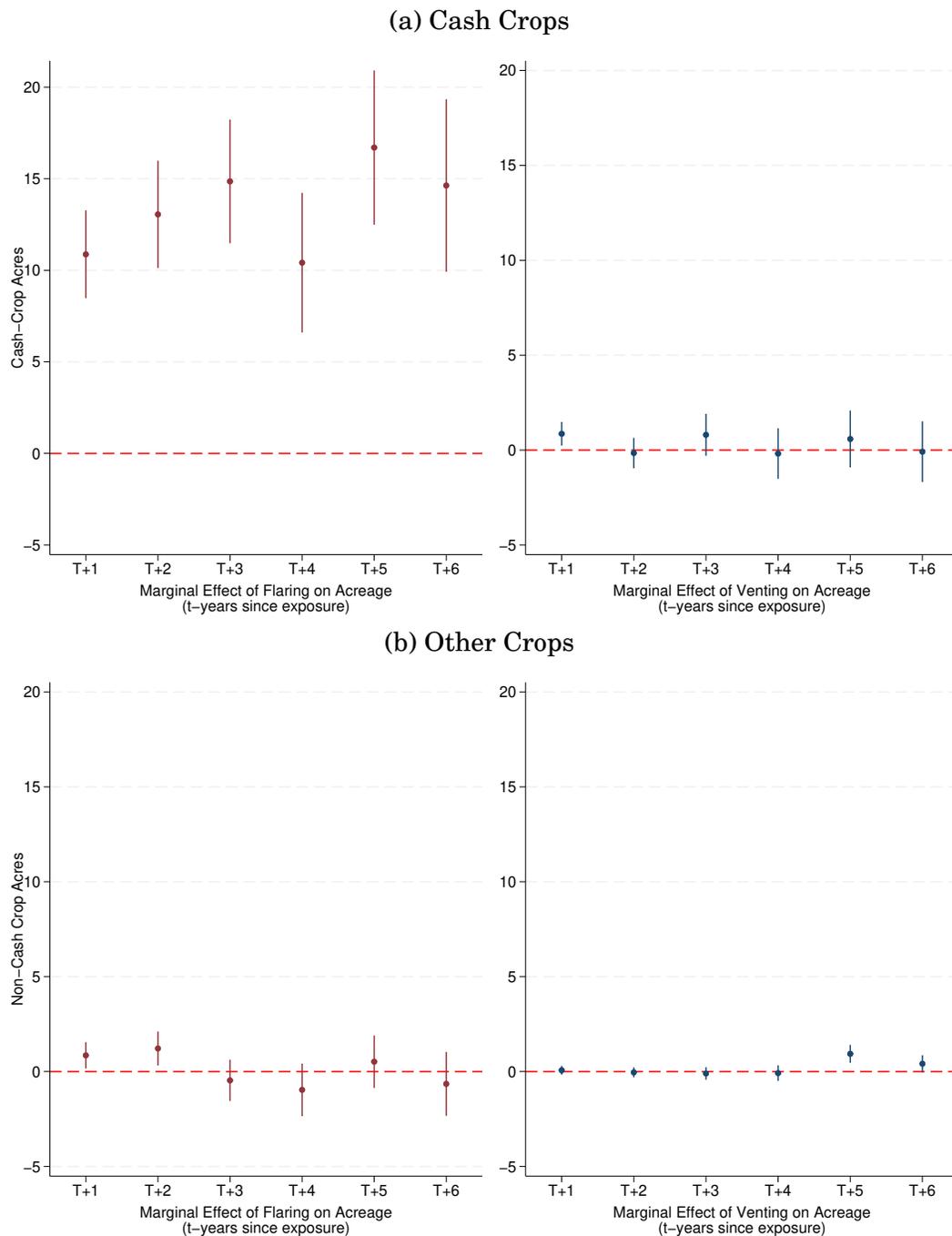
The estimates in Figures 5 and 6 and Tables 3 and 4 are derived from the regression omitting future values of flaring and venting. These results measure the cumulative change in farm size due to the first period exposure. Farmers may implement their expansion plans over several years, so these results capture the total effect of flaring and venting exposure. An alternative specific, one that includes future flaring and venting exposure, offers different insight, insight directly linked to persistence. By including future values of flaring and venting, we are able to isolate the one-period effects of exposure. This is what

is captured by (9).

Results for this alternative specification are shown in Figure 7. This figure measure the change in total acres planted as a result of a period t shock. Importantly, the pattern mimics that of Figure 5 in the first periods following the change. This is exactly what we would expect. As the shock propagates, though, slightly different dynamics appear. Purging the path of future exposure increases the later period growth. Magnitudes increase as the span from exposure increases, although those differences only become statistically significant different from early periods six years after initial exposure.

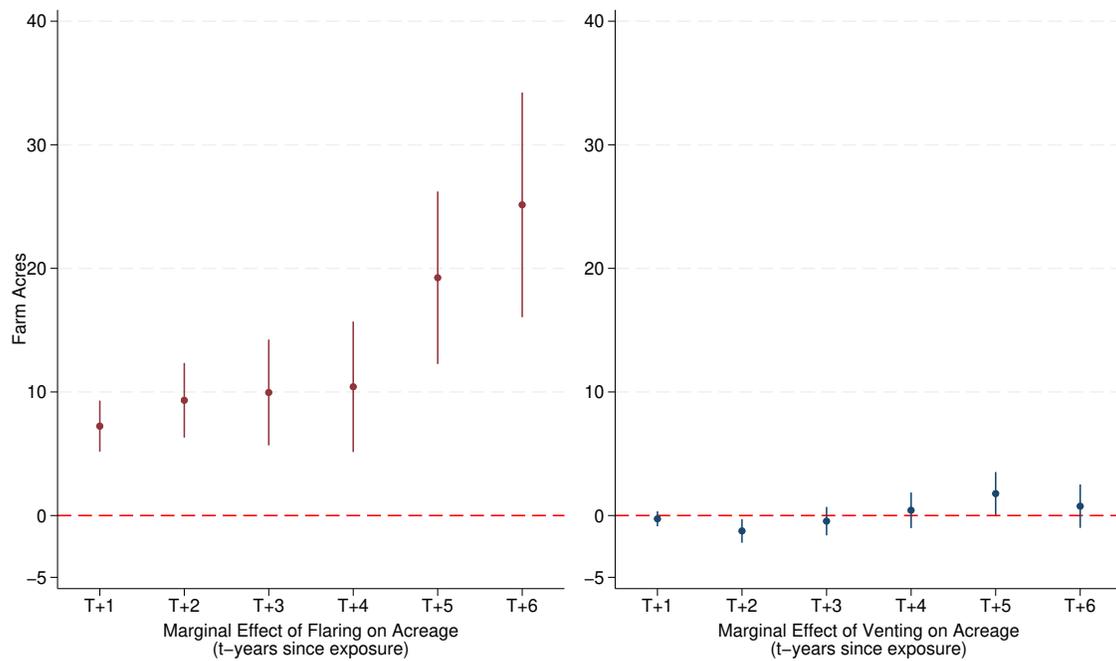
The interpretation of these results can be understood by comparing the paths in Figures 5 and 7. To reiterate, the two models, including and excluding future flaring and venting exposure, capture distinct estimands. Nonetheless, comparing their dynamic paths offers insight into the dynamics of farm investment. In particular, Figure 5 shows that ongoing exposure to flaring causes an initial increase in farm size that levels off at a new steady-state. Farms grow by 1.5% over six years. Conditioning on on-going exposure, however, isolates the onetime effect. This specification eliminates any cumulative adaption that may occur, illustrating a separate dynamic path. Farm size, after conditioning on future exposure, reaches a higher level as observable in Figure 7. There is greater responsiveness to a one-time shock for farmers than on-going exposure. Put differently, the response to on-going exposure diminishes. In both cases, farmers respond early. As exposure continues, however, responsiveness attenuates and farm expansions are limited compared with a state where there is no continuing exposure. Contrasting the results of Figures 5 and 7 is further consistent with our conceptual framework. Marginal costs of expansion increases. If there are adjustment costs to expansion, larger and larger yield gains are needed to warrant additions to acreage.

Figure 6: Investment Response to Flaring and Venting - Acres by Crop Type



Notes: Figure shows point estimates and 95% confidence intervals for the local projection-dynamic panel analysis outlined in Equation 8. Panel (a) measures total acres planted in cash crops (wheat, canola, and barley), 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 shows 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.

Figure 7: Investment Response to Flaring and Venting - Total Acres Planted, with Controls for Ongoing Treatment



Notes: Figure shows point estimates and 95% confidence intervals for the local projection-dynamic panel analysis outlined in Equation 9 in which we add controls for ongoing exposure to flaring and venting that occurs over the horizon. 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 $t - 1$. As with our main specification, all regressions employ a Blundell-Bond system-GMM estimator, with instruments of up to four-year lags, 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.

4.4 Connecting Investment to Asset Values

Farmers invest to increase the value of their farm. Land productivity is capitalized into farm values. High productivity land earns a premium over lower productivity acres – provided the level of productivity is permanent. Yet, the results from the previous section suggest that farmers are responding to *transitory* shocks to productivity by *permanently* increasing the size of their operations. This permanent increase in farm size – irrespective of the permanence of the productivity increases – can be rationalized if farmers obtain greater asset values as a consequence of flaring and venting exposure.

Put differently, it is costly to bring new farmland into production. Sulfur fertilization improves productivity. Improved productivity is temporary, however, because flaring is impermanent. Yet, we clearly observe that the temporary productivity improvements cause longer-term growth in farm size (and no response to negative venting shocks). So we seek to test whether farmers respond to the effects of flaring and venting because of its effects on asset values.

We approach this two ways. First, we use data on agricultural real estate transfers to test the relationship between flaring and venting and asset values. Data are at the municipality-level, and provide the average per-acre market value of all agricultural transfers that occur within a given year within a municipality. Using this information, we estimate the following hedonic regression (Bajari et al., 2012):

$$\begin{aligned} \Delta^h \ln(\text{Price/Acre})_{mt} = & \alpha_f^h \text{Flare}_{mt-1}^{50km} + \alpha_v^h \text{Vent}_{mt-1}^{50km} \\ & + \mathbf{W}_{mt-1}^{h'} \boldsymbol{\theta} + \rho_m + \gamma_t + e_{it+h} \quad h = 0, 1, 2, \dots, H, \end{aligned} \quad (10)$$

As in our investment analysis, we adopt a local projection approach that allows us to assess whether the hedonic relationship evolves over time. The dependent variable, $\Delta^h \ln(\text{Price/Acre})_{mt} = \ln(\text{Price/Acre})_{mt+h} - \ln(\text{Price/Acre})_{mt-1}$, is the change in log price per acre in municipality m between years $t - 1$ and $t + h$. We regress this price change on flaring and venting volumes that occur within 50km of the municipality’s center in year $t - 1$, controls for weather conditions within the municipality, and municipality and year fixed effects. We cluster standard errors to address potential serial correlation. The coefficients of interest in (10) are α_f^h and α_v^h . These represent the implicit price per mcm of flaring and venting

exposure on per acre agricultural land prices.

Results from the hedonic analysis are presented in Figure 8. The left-hand panel shows the effect of flaring on agricultural land prices and the right-hand panel shows the effect of venting. Flaring causes no meaningful change in land prices over the six-year horizon. Point estimates are small, ranging between plus or minus one-tenth of a percent, and the coefficients are also imprecisely estimated (with the exception of the first year following exposure, which is marginally significant). Flaring, despite increasing yields and leading to farm expansions, has no economically meaningful effect on asset values.

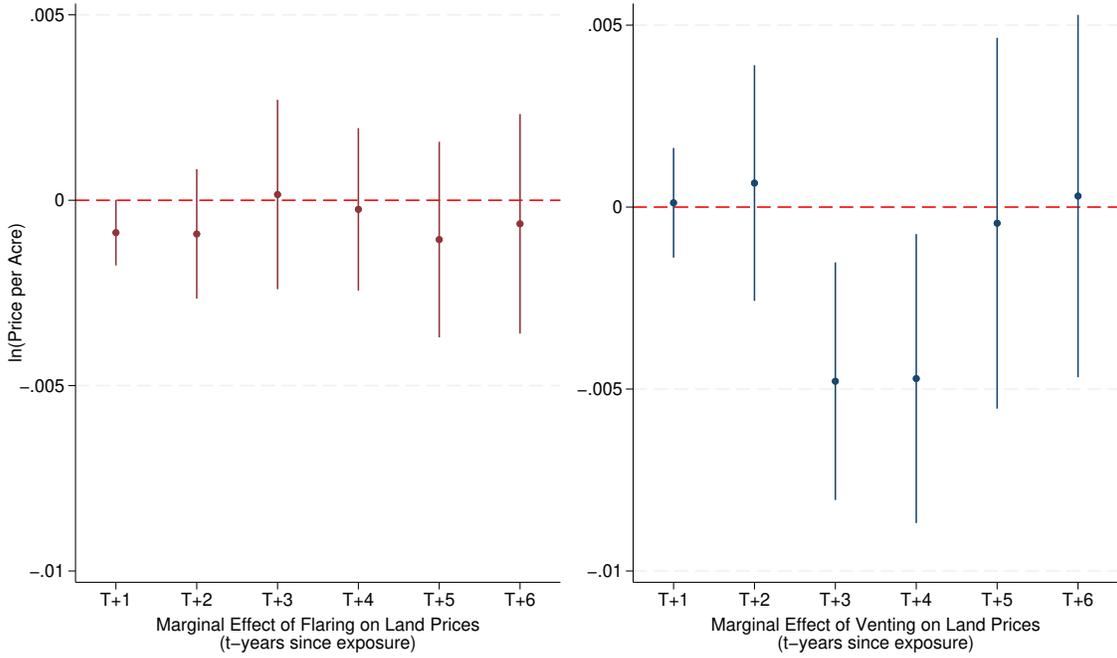
Exposure to venting is slightly less conclusive, but still not compelling. Changes in land prices are small and imprecisely estimated in years $t + 1$, $t + 2$, $t + 5$, and $t + 6$. In years $t + 3$ and $t + 4$, there are statistically significant negative effects, yet these are not economically meaningful. Moreover, we also estimate a version of (10) that controls for forward changes in flaring and venting exposure to isolate the one-time effect of exposure. In this alternative specifications, estimates in years $t + 3$ and $t + 4$ attenuate and become insignificant at conventional levels. Based on the hedonic analysis, venting, like flaring, does not appear to meaningfully affect agricultural asset values.

The lack of evidence from the hedonic regressions leaves a puzzle. It is unclear why farmers would expand their farms in response to transitory improvements in productivity if they cannot capitalize on larger farms.³⁴ The hedonic analysis has some important limitations, however. Chief among these is the potential for measurement error as a result of the regional aggregation in this data. To ensure our null finding in Figure 8 is not an artefact of measurement error, we corroborate the conclusions by invoking an implication of our conceptual framework.

As outlined in Equation 7, changes in farm value can be decomposed into the change in farm acreage plus the change in yield per acre. Flaring caused a 1.5% increase in farm size. Venting had no effect. We next require an estimate of the effect of expansion on average yields. Intuition suggests that farmers cultivate the most productive land first, expanding into marginal acres as op-

³⁴One argument may be that farmers *are* capturing the benefits for larger farms because they have more acres at the going rate (i.e., assets have increased). This argument implicitly assumes that farms were suboptimally sized prior to the expansion, however, essentially swapping one puzzle for another. We return to these ideas in the next section when we discuss mechanisms.

Figure 8: Effect of Flaring and Venting on Agricultural Land Values



Notes: Figure shows point estimates and 95% confidence intervals for the hedonic regressions outlined in Equation 10. The left inset shows the effect of flaring and the right inset the effect of venting. The dependent variable is the change in the log of agricultural land prices in year $t + h$ relative to year $t - 1$. The analysis is performed at the municipality level, with controls for weather conditions and municipality and year fixed effects. Standard errors are clustered by municipality.

erations grow. If farm expansion leads to a fall in productivity once the sulfur fertilization effect dissipates, then the acreage and yield forces could be offsetting one another.

We explore the potential post-expansion change in productivity by estimating the following regression:

$$\ln(\text{Yield}_{it}) = \omega \Delta \text{Acres}_{i,t-1} + \beta_1 \text{Flare}_{it}^{50km} + \beta_2 \text{Vent}_{it}^{50km} + \mathbf{W}_{it}\boldsymbol{\theta} + \rho_i + \gamma_t + \epsilon_{it}, \quad (11)$$

where $\Delta \text{Acres}_{i,t-1}$ is the farm's growth rate from the previous period³⁵ 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 (11), the coefficient ω is the correlation between the farm's growth rate and their subsequent crop yield,

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

conditional on weather and flaring and venting exposure. 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. A negative coefficient suggests that the permanent farm expansion is offset by a reduction in yield per acre, once the one-time sulfur fertilization effect is removed.

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. This points toward a potential explanation for the hedonic regressions and why farm values are not affected by flaring. Expansion reduces yields as newly cultivated land is less productive. Thus, when farmers respond to transitory flaring exposure through expansion, it comes at the cost of reducing overall average farm yields. Moreover, if expansion involves a fixed cost, then asset values cannot explain the observed hysteresis.

Table 5: Effects of Past Farm Expansion on Agricultural Yields

	(1) Barley	(2) Canola	(3) Wheat
$\Delta Acres_{i,t-1}$	-0.017 ^a (0.005)	-0.009 ^b (0.004)	-0.015 ^a (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.

5 Explaining Hysteresis

It is one thing to characterize hysteresis as the dynamic causal effect of an environmental shock. It is another to explain why the observed path arises. Compelling evidence points to sulfur fertilization as an explanation for the positive

effects of flaring on short-run agricultural yields effects. Finding a mechanism for farm expansion is more challenging. As a next step, we offer suggestive evidence that several financial variables – namely, insurance, cash flows and taxes – are the sources of hysteresis.

To start, the source of our data is AFSC, the provincial crop insurer. All farms in our data are covered by crop insurance. Crop insurance protects against negative on-farm quantity shocks, while allowing improvements in yields to be captured by the farmer. Because farmers are protected against downward quantity shocks, but are allowed to benefit from positive shocks, it is reasonable to expect asymmetric behavioural responses as a feature of the data. They are a property of insurance. Yet, while insurance can explain why farmers do not reduce farm size following a negative yield shock, it fails to explain why farms expand after a positive shock. To explain this, we turn to cash flow constraints and tax policy.

If farmers confront credit and cash flow constraints, resources may be limited. Farmers may not be able to expand at their desired rate. Good yields mean greater receipts, relaxing prospective cash flow limitations.

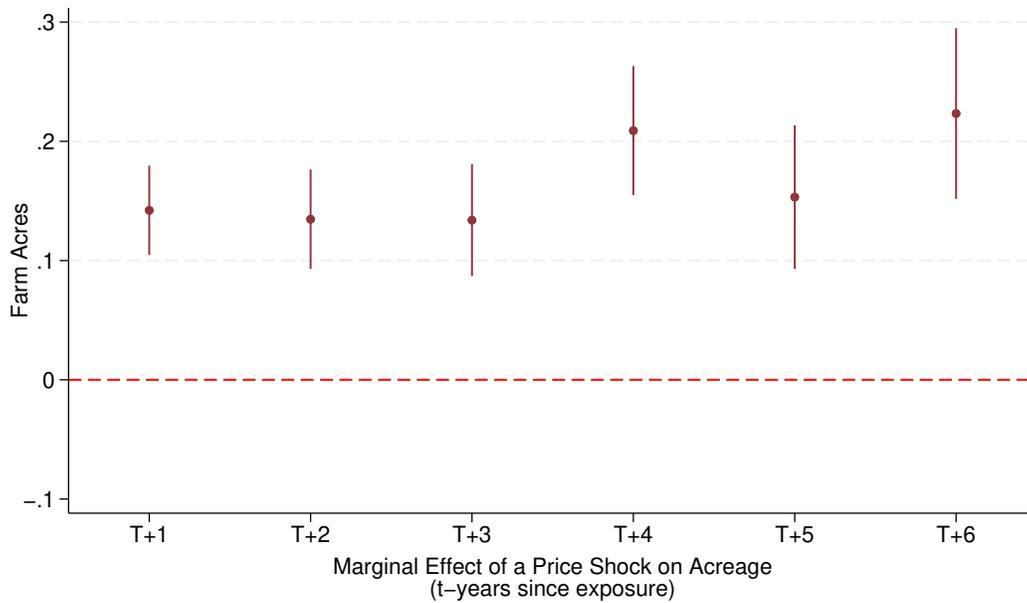
To test this mechanism we explore the effects of crop price-induced changes in cash flow. Prices for Albertan wheat, canola and barley were collected for August and September, typical harvest months. To generate farm-level variation, acreage-weighted average crop prices were calculated as:

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

where s_{it}^j is the share of total cash-crop acreage devoted to crop j , wheat, canola and barley. The variable Farm Price_{it} varies across farms within a given year because of differences in crop shares. It also varies within farms over time because of changes in crop shares and crop prices.

Using these crop-weighted, average farm prices, we estimate a local projection model. This model replaces the flaring and venting variables from the previous analysis with the new Farm Price_{it} variable. Figure 9 shows the results. Positive cash flow shocks, in this case due to higher prices rather than higher yields, generates a pattern very similar to the one observed when farms are exposed to flaring. Farms expand when cash flow constraints are more relaxed.

Figure 9: Investment Response to Crop Price Changes



Notes: Figure shows point estimates and 95% confidence intervals for the local projection-dynamic panel analysis of farm size in response to crop price changes. 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.

Next, while increased cash flow provides the resources needed to expand farms, it does not explain why farmers choose to allocate their resources to new acres rather than another activity. Canadian tax policy offers a hint for why farmers choose to grow their farms rather than opt for different investments. Land clearing and drainage receives favourable tax treatment under section 30 of the Canadian *Income Tax Act*. Farm expansions can be fully expensed in the year they occur. An example, from accounting firm BakerTilly shows how this works (VanGilst, 2019).

Consider the example of an Ontario farmer who spent \$100,000 in the spring of 2018 on tile draining a parcel of land that was formerly pasture. The combined 2018 corporate tax rate was 13.5 per cent. In the absence of section 30, the tile drainage would be an addition to the Class 8 UCC pool, eligible for CCA at a rate of 20 per cent, and subject to the half-year rule in the year of acquisition. If the expense

was included in class 8, the tax savings for 2018 would be \$1,350 (\$100,000 of tile drainage x 20 per cent CCA rate x 50 per cent for half-year rule x 13.5 per cent corporate tax rate). With the full deduction available under section 30, the tax savings for 2018 would be \$13,500 – ten times the savings compared to treatment as depreciable property (\$100,000 of tile drainage x 13.5 per cent corporate tax rate).

Thus, in this example, an investment in farm expansion, due to additional cash flows, yield \$12,150 in gains for the farmer. Thus, it could be the tax interaction with the relaxed cash flow constraint that encourages farm expansion. Moreover, while we demonstrated that marginal asset values do not increase following exposure to flaring, total assets do grow. Therefore, the favourable tax treatment offers a one-time benefit explaining why farmers choose to use their cash on farm expansion rather than allocate it to other uses – and explaining why we observe hysteresis.

Finally, Appendix E presents further analysis that bolsters the tax treatment mechanism. Table E.2 shows estimates where we regress total annual acres seeded for barley, canola and wheat in a province on the previous year’s mean effective tax rate. These models use province-by-year variation to see whether acres respond to taxation.³⁶ While coefficients are imprecisely estimated, results suggest that as effective tax rates increase, acreage increases. Farmers appear to manage their tax bill by adjusting farm size.

6 Conclusion

We study the effects of flaring and venting from oil production on: i) crop yields and ii) the subsequent investment decisions made by these farms. Using detailed regulatory and crop insurance data, we spatially link flaring and venting to agricultural production in the Canadian province of Alberta, a setting with

³⁶Of course, there are several notable caveats with these specifications. First, we do not observe the effective tax rates paid by farmers. They could be meaningfully different than the rates used in this analysis. Second, there is minimal within province variation in mean effective tax rates, so we are inferring effects from small changes. Finally, we seek to explain farm-level behaviour and aggregate acreage may average out many interesting dynamics. Notably, many provinces do not grow canola, so they are omitted from the models. Nonetheless, Table E.2 offers a hint that the tax interaction effect is observable in the data.

significant oil and gas and farming activities. We find that unanticipated and transitory pollution shocks from oil production spillover to generate short-run changes in agricultural yields. Flaring *increases* yields for wheat, canola, and barley, of between 0.3% to 0.7% per mcm of exposure, but venting *decreases* yields between 0.1% to 0.5% per mcm of exposure. In the years following exposure, farms then asymmetrically respond to these transitory shocks by making long-run changes in the number of acres planted. We find that farmers respond to the positive flaring shock by permanently expanding the size of their farms, but do not respond to the negative venting shock. The effects persist long after the initial exposure abates. Our analysis demonstrates the importance of connecting the physiological effects of pollution to investment and how hysteresis factors into our understanding of how agents adapt to environmental change.

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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). 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). Newly launched satellites, however, 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).

Flaring and venting is directly regulated in Alberta by the Alberta Energy Regulator (AER), the sole regulatory authority for energy resource development in the Province. 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.

The 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)* adopted by Alberta Environment and Parks (AEP) (Alberta Energy Regulator, 2022a). CASA has been an important driver of reduced flaring and venting volumes, for example the adoption of an annual global flaring target limit of 670 million cubic meters, beginning incrementally in 2000.

Directive 060 further makes clear that venting is not a suitable substitute for industry in trying to meet the flaring target limit and, though “significant volumes” are not defined, the *Oil and Gas Conservation Rules* require “significant volumes” of vented gas to be burned (S.8080(1)). More recently, the AER has put in place further restrictions on venting as part of the Province of Al-

berta's efforts to reduce methane emissions, a large portion of which come from venting (and thereof a large portion is from pneumatic equipment and fugitive emissions) in the upstream oil and gas industry.³⁷ 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, 2022a).

Overall, the efforts by CASA, the upstream oil and gas industry, and the AER have resulted in significant improvements in the amount of gas conserved (i.e., not released to the atmosphere). By 2002, the industry met the flaring target limit of 670 million cubic meters, exceeding the short term targets set by the AER (Alberta Energy Regulator, 2022a). *Directive 060*, per CASA recommendations, 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 NPV, the gas-oil ratio is high, or the AER otherwise requires it, wells must be shut in until they have put in place controls designed to conserve 95% of solution gas, and conserve at least 90% on an ongoing 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 kilomole (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 kilomole 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

³⁷See, <https://static.aer.ca/prd/documents/ab-uog-emissions-inventory-methodology.pdf>.

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*, which 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).

The AER has recently put in place additional restrictions on emissions in the Peace River Area, with the objectives of eliminating any routine venting, preventing non-routine venting, reducing non-routine flaring and fugitive emissions, and targeting 95% conservation of solution gas.

Directive 060 was amended in 2018 and again in 2020, under the direction of the Government of Alberta, to include requirements to reduce methane emissions. These requirements address the primary sources of methane emissions from Alberta’s upstream oil and gas industry: fugitive emissions and venting, which includes emissions from compressors, pneumatic devices, and glycol dehydrators. The requirements also include improved measurement, monitoring, and reporting of methane emissions. In 2018, significant changes were also made to the fuel, flare, and vent gas definitions in Directive 060. The definition changes were made so that gas that was used in equipment, but ultimately flared or vented, was captured as such and not reported as fuel. For example, gas used for pneumatics was previously reported as fuel. However, since this gas is ultimately vented to atmosphere, it was determined that emissions were better represented if that gas was reported as vent.³⁸

There are also regulations on the testing and monitoring of orphan wells in the province.³⁹ However, the majority of emissions are from active wells, which

³⁸<https://static.aer.ca/prd/documents/sts/ST60B-2020.pdf>.

³⁹For example,

7.060(1) This section applies to any well which produces gas containing more than 10 moles per kilomole hydrogen sulphide, or such higher or lower ratio as the Regulator may stipulate with respect to any well, pool or area, having regard to

is our focus.

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 regions of the province of Alberta.

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 per farm exposure to flaring and venting for different radii. As is evident, exposure is fairly constant once farms are within 20-30km of a flare stack or venting facility.

C Additional Results and Robustness Checks: Short-Run

C.1 Background on Plant Physiology

C.1.1 Plant Science Literature

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

pressures, nature of production, remoteness of the area and other circumstances.
(1.5) Where no gas analysis has been taken from the well within the preceding 12-month period, gas from the formation produced at the well shall be tested at the commencement of flaring to determine the hydrogen sulphide content.

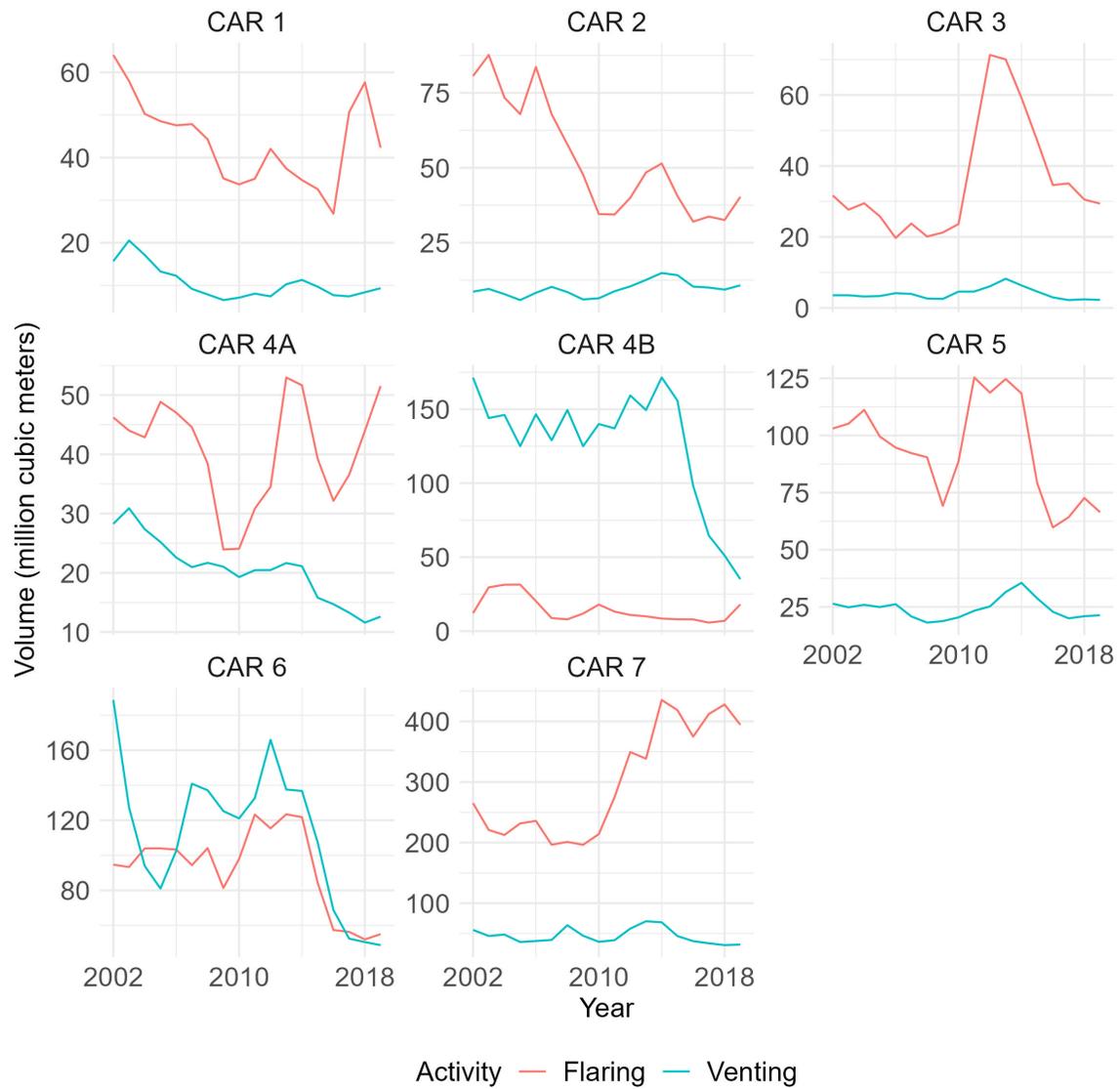


Figure B.1: Trends in flaring and venting activity in Alberta by Census Agricultural Region (CAR), 2002-2019

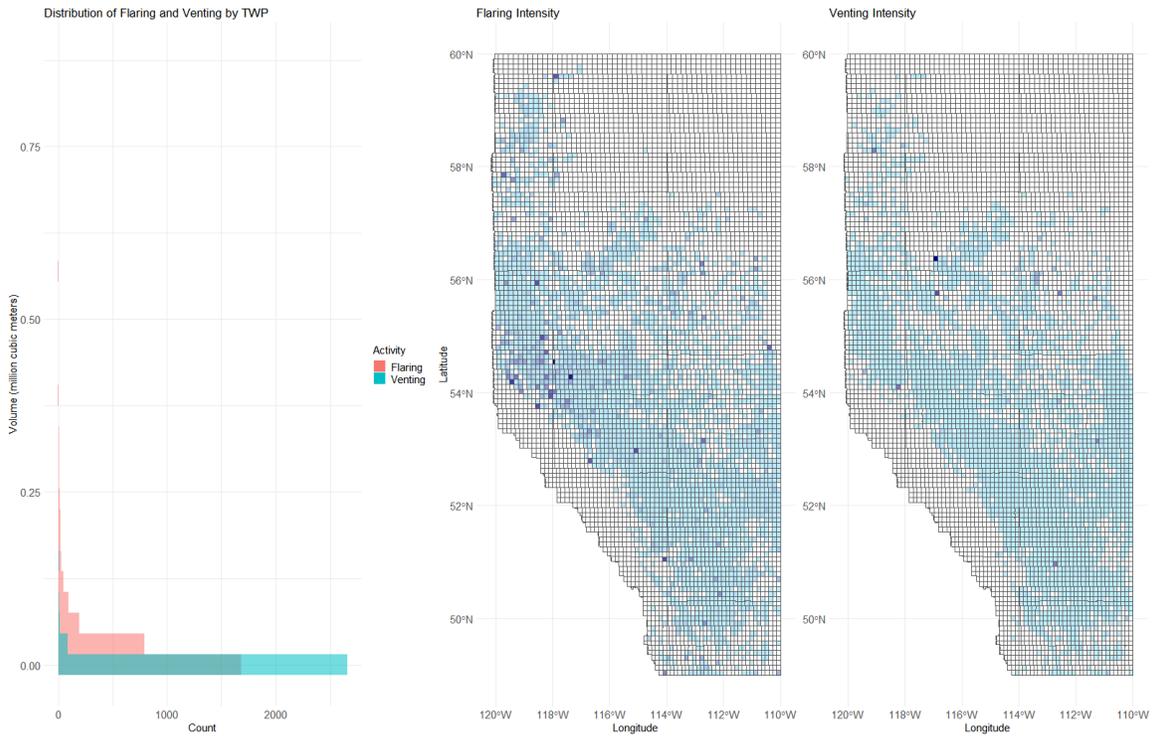


Figure B.2: Distribution of flaring and venting activity in Alberta, 2002-2019

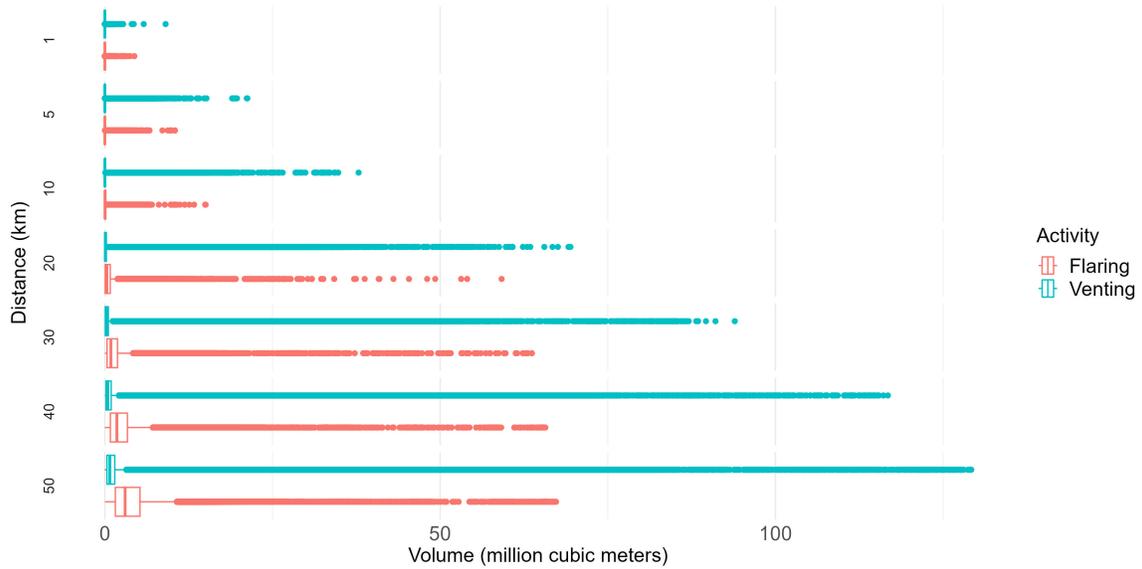


Figure B.3: Boxplots of flaring and venting exposure at varying distances, 2002-2019

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.

The major air pollutants, sulfur dioxide, nitrogen oxides, and ozone, are toxic to plants (i.e., phototoxic), 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). In addition to their direct toxicity to plants, 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).

Finally, particulate matter can affect plant yields since deposits on plant leaves can physically reducing the amount of ultraviolet light available for photosynthesis, and smaller particulate matter can clog plant stomata, reducing carbon dioxide intake and photosynthesis rates (Kulshrestha and Saxena, 2016; Li et al., 2019).

C.1.2 Air Pollution and Crop Yields

Following decades of experimental research establishing the link between air pollution and crop damage and yield losses, the 1980s saw a shift in research from the lab to the field with the publication of several econometric studies and the startup of a U.S. EPA-funded research program and community known as the National Crop Loss Assessment Network (NCAN), which focused on field experiments, economic assessments, and evaluation of causal relationships to advance scientific understanding and inform updated National Ambient Air Quality Standards (NAAQS) (Heck et al., 1982; Westenbarger and Frisvold, 1995).

Some of the earliest econometric research to estimate crop damages associated with air pollution was conducted by Leung, Reed and Geng (1982) and Garcia et al. (1986), who estimated the damages from ozone exposures on crops in Southern California and Illinois, respectively, finding a negative effect of ambient ozone concentrations on yields. Continuing this tradition, Westenbarger and Frisvold (1995) used farm-level data to examine the impact of ozone pollution on yields of corn and soybean in the eastern United States in 1990, similarly finding a negative effect. These significant findings demonstrated that *ambient concentrations* of air pollutants were meaningfully affecting crop yields, extending the previous controlled experimental findings as well as evidence from more isolated cases of higher levels of pollutants from local industrial activity.

As described in the main text, the past few years have seen a resurgent interest in estimating the relationship between air pollution and crop yields, partly motivated by the availability of new data sources such as estimates of air pollutant concentrations from satellite data. Using estimates from satellite data, Lobell, Di Tommaso and Burney (2022) showed a negative relationship between nitrogen oxide concentrations and crop greenness across China, India, Western Europe, and North and South America, noting that the effect was greatest in areas where low nitrogen oxide concentrations limited ozone formation. Liu and Desai (2021) combined satellite estimates of aerosols, air pollutant monitor data of ozone, and weather data to estimate the combined impact of aerosols, ozone, and heat on maize and soybean yields in the US from 1980 to 2019. They found a negative association of aerosols and ozone with maize and soybean yields and significant negative interaction effects of both pollutants with heat. Lobell and Burney (2021) use a combination of air pollutant

monitor data (for ozone, sulfur dioxide, and particulate matter), satellite-based estimates of nitrogen dioxide, carbon dioxide, county-level yields and satellite crop greenness-derived yields for maize and soybeans to estimate the impact of air pollution, finding that air pollution reduced yields by 5% over 1999 to 2018 and that current levels of nitrogen dioxide and particulate matter may reduce crop yields more than those of ozone and sulfur dioxide. Similarly, McGrath et al. (2015) found a negative association between ozone concentrations and maize and soybean yields (-10% and -5% respectively) in the US for 1980 to 2011, focusing only on rain-fed fields. Hong et al. (2020) looked at perennial crops in California rather than major crops such as soy and maize, finding ozone concentrations were associated with negative effects on yields ranging from -2% to -22%, depending on the crop.

In terms of econometric studies examining the effect of flaring and venting on agriculture, none to our knowledge exist. A number of observational and experimental studies have been published, many from Nigeria, a major hot spot of oil and gas and flaring activity. For example, Odjugo, Osemwenkhae et al. (2009) tested experimental plots at varying distances from a natural gas flare, finding increased temperatures and reduced humidity and soil moisture closer to the flare and maize yield reductions of 58% to 76% from 2km to 500m from the flare. Atuma and Ojeh (2013) similarly used an experimental approach to evaluate the effect of a natural gas flare on cassava yield, finding a negative effect of proximity to the flare on cassava yield. Sharma et al. (2011) also studied the effects of flaring on rice experimentally in India, finding reduced yields closer to the flare and different sensitivities depending on the variety of rice.

C.2 Flaring and Air Pollution

Flaring and venting of solution gases results 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 generally 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 compo-

sition 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 (Stroscher, 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 (Stroscher, 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) (Stroscher, 2000; Leahey, Preston and Stroscher, 2001). Estimates of combustion efficiency of flares vary considerably, ranging from as low as 62% (Stroscher, 2000; Leahey, Preston and Stroscher, 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).

Estimating specific emissions from gas flares is complicated by data limitations on the underlying composition of the gases being combusted, and challenges associated with direct measurement of emissions from flares, which have historically been overcome through the use of remote sensing approaches (Haus et al., 1998; Allen and Torres, 2010; Johnson, Devillers and Thomson, 2011) and chemical material balance approaches (Sonibare and Akeredolu, 2004; Umukoro and Ismail, 2017). While studies of gas flares in laboratory settings have contributed to understanding emissions, there may be important differences between laboratory studies that estimate emissions from flares of known gases in known and controlled conditions, and emissions from active flares of (potentially) unknown and varying gases in real-world and varying conditions; directly measuring emissions from active flare sites in the upstream oil & gas industry remains challenging but necessary to fully understanding the associated emis-

sions (Johnson, Devillers and Thomson, 2011). A few studies estimating flaring emissions, however, have been conducted in industrial settings or on industrial-size flares with the use of sampling equipment to measure the components of the flare plumes (McDaniel and Tichenor, 1983; Strosher, 2000).

Recent studies on flaring have provided further insights into emissions, showing black carbon emissions to be variable and related to the gas heating value (McEwen and Johnson, 2012; Fortner et al., 2012; Conrad and Johnson, 2017; Weyant et al., 2016), and variations of an order of magnitude in emissions of nitrogen oxides in full scale flare tests (Torres et al., 2012) and in operational flares in Texas (McDaniel and Tichenor, 1983). Further, direct emissions of volatile organic compounds have been evaluated in Alberta, Canada (Strosher, 2000) and in Texas, United States (Allen and Torres, 2010), and elevated levels of VOCs have been measured near OG operations in Colorado, Wyoming, Arkansas, and Pennsylvania (Gilman et al., 2013; Macey et al., 2014).

Nitrogen oxides and volatile organic compounds are ozone precursors and react in the presence of sunlight and heat to form ground-level ozone, a secondary air pollutant (Ainsworth et al., 2012). Since natural gas flaring emits both nitrogen oxides and volatile organic compounds, researchers have modeled the potential impact of these emissions on ozone levels near oil and gas operations, with Al-Fadhli et al. (2012) estimating changes in ozone concentrations in Houston, Texas at between 1 and 15 parts per billion (ppb) and Olaguer (2012) estimating ozone changes from a simulated 2-hour flare around 3ppb between 2 and 8km downwind (with a temporary peak 16km downwind from the flare of over 10ppb).

C.3 Robustness Checks

Table C.1 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.

<i>Panel A: Barley Yields (kg / acre)</i>						
	No Controls		Weather Controls		Weather + F.E.	
	Est.	S.E.	Est.	S.E.	Est.	S.E.
Vent	-0.006	0.000	-0.002	0.000	-0.005	0.001
Flare	-0.005	0.001	0.000	0.001	0.007	0.001
Observations	117 193		117 193		117 193	

<i>Panel B: Canola Yields (kg / acre)</i>						
	No Controls		Weather Controls		Weather + F.E.	
	Est.	S.E.	Est.	S.E.	Est.	S.E.
Vent	0.000	0.000	-0.001	0.000	-0.001	0.000
Flare	-0.006	0.000	0.001	0.000	0.003	0.001
Observations	130 421		130 421		130 421	

<i>Panel C: Wheat Yields (kg / acre)</i>						
	No Controls		Weather Controls		Weather + F.E.	
	Est.	S.E.	Est.	S.E.	Est.	S.E.
Vent	-0.002	0.000	-0.002	0.000	-0.003	0.000
Flare	0.004	0.000	0.006	0.000	0.006	0.001
Observations	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 C.1: Effect of Flaring and Venting on Agricultural Yields, Alternative Specifications

D Additional Results and Robustness Checks: Long-Run

E Additional Tables and Figures on Mechanisms

	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 E.2: Effect of Mean Effective Tax Rates on Seeded Acres, Provincial Level Data (000s acres)