Rapid Increases in Methane Concentrations Following August 2020 Suspension of the US Methane Rule *

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Abstract

In August 2020, the Trump Administration removed Obama-era federal requirements that oil and gas firms detect and repair methane leaks. We merge GIS coordinates of 1,193,575 wells, 478 natural gas processing facilities, and 1,367 compressor stations to geo-identified methane concentrations from the European TROPOMI (satellite instrument). Using a difference-in-differences design, we find a large, prompt increase in US methane emissions at oil and gas infrastructure sites following the August 2020 rollback relative to areas without such infrastructure. Average methane concentrations increased by 5 parts per billion (ppb), or one quarter of a standard deviation. The number of high-methane emission events from the oil and gas sector more than doubled relative to the coal sector, which did not experience the rollback. Gas producers and distributors have argued they face an overriding incentive to minimize fugitive methane emissions and venting without regulation – so as to recover and sell a valuable commercial product. The large and nimble response to federal policy we find – together with basic microeconomic theory – indicate otherwise and provides empirical support for policy's central role in curbing global methane concentrations.

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1 Introduction

Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5 °C. (IPCC, 2021)

Methane accounts for 30% of the increase in global temperatures since pre-industrial times (United Nations, 2021). Not only are global methane concentrations increasing, they have been increasing at an accelerating rate. Jackson *et al.* (2020) find that fossil fuels and agriculture contribute equally to increased global methane concentrations. Howarth (2022) argues that natural gas is a larger contributor to the global methane increase than agriculture, using aircraft, satellite, and tower-based methane measurements from natural gas systems. Particularly in the US, fossil fuels are the preponderant driver of increasing methane emissions. Jackson *et al.* (2020) find that 80% of the methane increase in the US since the early 2000s to 2017 came from fossil fuel-related methane emissions through fugitive pipeline leaks, venting, etc. Increased methane emissions parallel the massive increase in US fossil fuel production enabled by new fossil-extraction technologies, including hydraulic fracturing (fracking). The US is now the world's top producer of oil and gas.

Improvements in methane measurement have lead to large upward revisions in estimated methane emissions from the oil and gas sector. For example, Alvarez *et al.* (2018) validated ground-based methane measurements with aircraft observations and found that emissions from the natural gas supply chain were 60% higher than that estimated by the US EPA. Using satellite measures and focusing on the Permian basin in Texas and New Mexico, Irakulis-Loitxate *et al.* (2021) highlight the importance of "extreme point sources", which account for a large share of overall emissions. Surprisingly, newer oil and gas facilities are major emitters, in large part due to inefficient flaring operations. Overall, the satellite estimates of methane emissions from the Permian Basin are roughly double previous "bottom-up" estimates. Under a revised methane leakage rate - 9.4% of gross gas production (Chen *et al.*, 2022) - and given that methane causes 86 times more global warming than an equivalent amount of CO_2 over a 20 year period, natural gas has a greenhouse gas impact comparable to coal (Alvarez *et al.*, 2012; Ladage *et al.*, 2021).[1]

"Ultra" emission events, defined as methane emissions exceeding 25 tons per hour, were not detectable until 2019 on a global scale. Irakulis-Loitxate *et al.* (2022) note that: "new satellite methods promise a revolution in the detection and monitoring of methane point emissions worldwide." Roughly two thirds of these high-emission events stem from point sources of oil and gas infrastructure (Lauvaux *et al.*, 2022). After Turkmenistan and Russia, the United States is the third largest national source of ultra emissions events, this despite the exclusion of ultra emissions events in the Per-

[1] Ladage *et al.* (2021) conclude that a methane leakage rate of 4.9% would make natural gas more harmful than coal in terms of the climate impact. Alvarez *et al.* (2012) estimate the threshold at 3.2%. The leakage rate of 9.4% exceeds both estimated thresholds.

mian basin due to interference (Lauvaux *et al.*, 2022).[2,3] Ultra emission events are an increasing focus of resarcher and press attention, e.g. *The Guardian*, because of their large (and dramatic) contribution to total fossil industry emissions.

Mohlin *et al.* (2022) highlight the low and even negative net abatement costs for methane emissions from the oil and gas sector. As radiative forcing of methane was revised upward by 25% (Etminan *et al.*, 2016), the social cost of methane has been estimated at $933 per ton (Errickson *et al.*, 2021). This estimate also varies significantly depending on the income level of a region (Errickson *et al.*, 2021), raising additional social justice concerns. Lauvaux *et al.* (2022) project net savings in the US from eliminating ultra emissions events. Our analysis focuses on an abrupt regulatory change in summer 2020.

2 2020 Rollback of US Methane Policy

On August 13, 2020, the Environmental Protection Agency (EPA) issued two final rules rolling back the New Source Performance Standards (NSPS) for oil and gas facilities.[4] The NSPS[5] dates back to 1970, when the Clean Air Act's section 111 authorized the EPA to develop and implement pollution standards for specific categories of stationary sources. Our policy of interest is the NSPS for oil and gas facilities. These facilities were included in the NSPS priority source list in 1978.[6] The NSPS regulates the oil and gas sector's Hazardous Air Pollutants (HAP) and Greenhouse Gases (GHG) emissions. Sources subject to NSPS are required to conduct an initial performance assessment to substantiate their adherence to emission standards. To demonstrate continuous compliance, NSPS further requires the utilization of continuous emission monitoring systems. Emission sources may also be required to monitor control device operating parameters to demonstrate continuous compliance. Consistent with EPA's Clean Air Act Stationary Source Compliance Monitoring Strategy, NSPS sources that meet the Clean Air Act definition of "major source" generally receive a full compliance evaluation by the state at least once every two years.

Natural gas supply facilities can generally be divided into four parts/stages: production, processing, transmission, and storage. All four stages have potential leakage of methane during the production process, and are potentially affected by these two rules in August 2020. The first rule is the final policy amendments to the 2012 and

[2]The close geographic proximity of distinct components of oil and gas infrastructe complicate source assignment in the Permian basin.

[3]The Permian basic accounts for roughy one third of US oil and gas industry emissions (Alvarez *et al.*, 2018).

[4]See EPA website: https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry/epa-issues-final-policy-and-technical. This section summarizes the rules based on the EPA's amendments content with a special focus on methane emissions. Interestingly, larger oil and gas firms, including Exxon, Shell, and BP, opposed elimination of the Obama-era rule.

[5]Here we focus on the Clean Air NSPS. NSPS is also used in the Clean Water Act where it refers to standards for water pollution discharges of industrial wastewater to surface waters.

[6]The priority list is the "Priorities for New Source Performance Standards Under the Clean Air Act Amendments of 1977" published by the EPA. It includes "Crude Oil and Natural Gas Production Plant" as one source category.

2016 NSPS. It focused on the sector coverage of methane emission standards. The second is the final technical amendments to the 2016 NSPS. It focuses on compliance, including fugitive emission monitoring and reporting.

Under the final policy amendments, transmission and storage segment were removed from the NSPS source list, which means all their emissions, including both HAP and GHG including methane, are rescinded from the NSPS regulation. The federal regulatory actions will no longer cover these two segments, although they may still be regulated by state or local environmental agencies. Regarding production and processing facilities, the amendments separately rescind the methane-specific requirements of the NSPS, while other non-methane GHG and HAP emissions continued to be regulated. To sum, the final policy amendments rescinded regulations to a greater extent for transmission and storage segments. In later sections, we consider all four of these natural gas segments as facilities, and separately compare the responses of transmission and storage facilities with those of others.

3 Data

3.1 Methane Measurement

Methane data come from the TROPOMI (the TROPOspheric Monitoring Instrument) on board the Sentinel 5 Precursor (S5-P) satellite. Launched in 2017, it provides daily global coverage, and measures radiances between the ultraviolet (UV) and shortwave infrared (SWIR) in eight bands. The methane product is retrieved from radiance measurements in TROPOMI's SWIR bands with a spatial resolution of 7km. TROPOMI has proven adept at measuring methane levels (e.g., Hu *et al.*, 2018; de Gouw *et al.*, 2020). We use column-averaged methane mixing ratios and construct weekly data on a 0.1° grid.

3.2 Natural Gas Facility Information

We use detailed GIS coordinates to assign grids with and without natural gas facilities. We focus on methane grids with natural gas facilities, including production wells, processing plants, pipelines, and compressor stations. Locations of these facilities are obtained from the US Energy Information Administration (EIA).[7] EIA reports 1,193,575 wells in total.[8] 398,849 are located in Texas and 104,143 are in Pennsylvania. California, Kansas, and Ohio have more than 90,000 wells. EIA reports 478 processing plants and 1367 compressors in the US.

3.3 Emission Events

We use the ultra-emission event data derived from TROPOMI (Lauvaux *et al.*, 2022). This dataset includes detected methane plumes greater than 25 parts per billion (ppb)

[7] Map layers of most oil and gas facilities are available from the EIA website: https://www.eia.gov/maps/layer_info-m.php

[8] We are not able to observe well-level production, so we could not separately analyze high versus low-production wells.

averaged over several pixels around the globe, defined as "emission events". There are more than 1,800 observed emission events from 2019 to 2020 worldwide. Among these events, we use the 326 events that occurred in the oil and gas sector in the US (Lauvaux *et al.*, 2022). Each event is associated with the date the plume was observed and the estimated coordinates of the sources. The coordinates are estimated using the HYSPLIT model simulation that best fit the detected plume (Stein *et al.*, 2015).

To verify the basic consistency of emission event and methane concentration data sources, we flag pixels with at least one emission event, and compare methane levels in event pixels with non-event pixels. Table 1 displays correlation test at the grid-week level. Positive, large and significant estimates confirm that event pixels have higher methane concentrations by around 17 ppb, and only slightly smaller than the standard deviation of methane concentrations. Results are robust to state, annual, and flexible seasonality (fixed) effects.

4 Estimation

For regressions Tables 2 and S1, we estimate two basic types of difference-in-difference regression models. Table 2 assesses how the post August 13 methane levels changed in 2020 versus 2019. In particular, in column (2) we estimate using OLS:

$$Methane_{pwy} = \beta_1 Post_w + \beta_2 Y2020_y + \beta_3 Post_w * Y2020_y + \tau_w + \gamma_p + \epsilon_{pwy}. \qquad (1)$$

The parameter of interest is β_3: how much more methane levels changed after August 13 in 2020 than in 2019. p indexes the pixel, w calendar week, and y the year. τ_w denote fixed effects for each of the 4 quarters of the year (to account for seasonality). Likewise, γ_p denote fixed effects for each pixel. Their inclusion means we are restricting empirical comparisons to changes within each pixel in estimating β_3.

Table 3 assesses how much more emissions changed after August 13 in the oil and gas sector relative to other sectors. Utilizing the mapping of emission events to their specific sources, we leverage an alternative "control group" to equation 1 that is is less susceptible to confounding from common shocks within 2020. Column (2) is estimated as folllows:

$$\#\ emissions\ events_{st} = \theta_1 Post_t + \theta_2 OG_s + \theta_3 Post_t * OG_s + \tau_t + \gamma_t + \epsilon_{st}. \qquad (2)$$

Post is an indicator that equals one if time t is after August 13, 2020. The parameter of interest is θ_3: how many more/fewer daily emission events there were in the Oil and Gas sector after August 2020. t indexes month-by-year and s the sector. τ_t denote fixed effects for each each day of the week. Likewise, γ_t denote fixed effects for of the four quarters in a year (to account for seasonality).

Table S1 estimates equation (2) but using the pixel-level data analyzed for Figure 1 and Table 2. We restrict the sample of pixels to be those with at least 1 high-emissions event from January 1, 2019 to August 13, 2020. Thus we are focusing on pixels that were relatively "leaky" before the methane rule was suspended.

5 Results

5.1 Ambient methane

We present our basic results in time series figures of methane concentrations and methane emission events. We then estimate regression models to: a) account for the role of other factors or confounders that may drive these graphical patterns; b) estimate standard errors and thereby the statistical significance of changes following the August 2020 policy change.

Figure 1 plots the weekly average methane concentrations from February 8, 2019 to September 3, 2021. We restrict the sample of pixels to those with a least one drilling well, processing plant, distribution pipeline or compressor station. The vertical line indicates the week of August 13, when the methane rule was suspended. Broadly speaking, there is an upward trend over time, with variation around this trend. One of the larger increases over this time period follows the August 13, 2020 lifting of the methane rule.

In Figure S1 Panel A, we separately plot the time series for 2019 and 2020 to better compare these two years during the same calendar weeks. The gap between the red and blue lines remains positive and stable before August, confirming an annual increase in methane and a parallel trend before the policy implementation. The gap is larger after August. This graphical evidence supports our hypothesis that the ambient methane level increase after August 2020 was atypical. Panel B further adds year and month fixed effects and plots the residuals. The two residual series show similar trends before August, followed by a striking increase in ambient methane after August 2020.

Table 2 restricts the sample period to be closer to the rule change: from February 8, 2019 to December 31, 2020. We do not include data from 2021 because the 2020 rollback was nullified by the Senate in April 2021 and by the House in June 2021. Estimates in the first two rows indicate that emissions were significantly higher both after August 13 (in both 2019 and 2020) and on average in 2020. Beyond these "main effect" differences, the coefficient on the $Post \times Y2020$ interaction term gives the additional change in methane concentrations after August 13, 2020. That is, after accounting for quarterly seasonality present in 2019 and the annual increase from 2019 to 2020, emissions were 4-5 ppb higher after August 13, 2020, or roughly a quarter of the standard deviation in methane concentrations. The standard errors indicate that these estimates are quite precise. Furthermore, the estimated increase does not change substantially with varying regression control strategies, e.g. including a dummy variable for each pixel and thereby restricting comparisons to be within pixel over time. We can also allow seasonality to vary flexibly by each US state without altering the basic impact estimate. Figure 2 shows the frequency distribution of methane levels near treated pixels before and after the policy rollback. Consistent with results in Table 2, there is a clear mean shift in methane levels, from 1860.3 ppb to 1876.5 ppb.

As a robustness check, we instead run a single difference regression using the same sample and include one treatment *Post* on the right-hand side. *Post* is set to one for weeks w after August 13, 2020 and zero before, i.e. the same as $Post \times Y2020$ in equation (1). Results in Table S2 show positive and precise estimates on *Post*, suggesting significant methane increases after the policy rollback.

Our EIA data specify the type of natural gas infrastructure. We find that ambient methane increases were largest near wells and pipelines, as shown in Table S3. This could be due to high sporadic leaking potentials or the high marginal costs of leakage abatement. Additionally, it may be easier for companies to reduce their leakage monitoring, control, and abatement activities near wells and pipelines. In contrast, methane changes near processing plants and compressors are not statistically different from zero or are negative, which may suggest that leaks at these locations are more responsive to long-term capital investment decisions.

Around this average concentration increase, did "leaky" locations become particularly "leakier" after the policy rollback? We focus on the subset of pixels that are in the top 5% of methane concentrations in the pre-rollback period. Table 4 reports estimated results. Coefficients on the interaction term $Post \times Y2020$ show 6-7 ppb higher emissions in the post-period, or one third of a standard deviation.[9] Compared with the pooled results in Table 2, highly emitting pixels indeed have larger estimated leaks after rollback. Emitters may have been under stricter regulation and monitoring before the rollback and therefore respond most to reduced stringency. They may also be facilities with a higher incentive to leak due to higher costs of leak abatement. This heterogeneity by baseline concentration motivates our analysis of ultra-emission events.

Since the policy amendment removes transmission and storage facilities from the NSPS source list, we expect greater methane leakage from these two subgroups compared to other natural gas facilities. In Table S4, we separately estimate equation (1) for the two subgroups and others. In Panel A, estimates of the interaction term $Post \times Y2020$ show a 4.8 ppb higher methane level in the post-period in pixels with transmission or storage plants relative to the same calendar period in 2019. In Panel B, pixels with other facilities also experience an increase in ambient methane by 4.0 ppb, which is smaller than that in Panel A. In Table S5, we conduct a triple difference analysis and confirm a significant estimate on $Post \times Y2020 \times Facility$, indicating higher methane increases in pixels with storage and transmission plants compared to pixels with other facilities. Estimates on $Post \times Y2020$ remain positive and precise. This suggests that even with only two types of facilities removed from the NSPS source list, facilities still within the NSPS receive less regulation on leakage from fossil fuel companies, leading to an industry-wide rollback in methane regulation due to the policy amendment.

As a robustness check, we check alternative sources of methane emissions including landfill facilities and Concentrated Animal Feeding Operations (CAFOs). Given their important roles in total methane emissions in the US, this practice helps to rule out the potential confounding channel that may cause the observed methane increase after August 2020. Coordinates for 10,081 landfill sites are obtained from the Homeland Infrastructure Foundation-Level Data (HIFLD). CAFO intensity at the county level is obtained from the USDA Census of Agriculture. We drop pixels with at least one landfill facility and drop counties in the top quartile of CAFO intensity. Results in Table

[9]Likewise, these Table 4 impacts are also higher relative to the pixel mean methane concentrations.

S6 are very similar to those in Table 2, confirming our identified methane increases are not driven by the waste sector and animal farming sources.

5.2 Ultra-emission events

Figure 3 and Table 3 focuses on major methane emission *events*. Figure 1 shows the monthly count of major emission events for 2019-2020. Prior to August 2020, the number of emissions events per month appears similar in the oil and gas versus coal sectors. This similarity changes radically after August 2020, when we see more emissions events in the oil and gas sector. Table 3 recasts this analysis at the daily level, and thereby leveraging the specificity of the August 13 rollback date. The coefficient on the interaction of $Post \times OG$ gives the additional change in the daily number of emissions events in the oil and gas sector after August 13. It indicates a .12 to .15 increase in the daily count of emissions events. This estimate is statistically distinguishable from 0 and is robust to the alternative sets of controls for potential confounders, e.g. seasonality or day of week fixed effects. It is also large relative the baseline mean of .09.

To test the validity of our design, we consider the pre-trend in ultra-emission event count in the coal and oil and gas sectors. We add interaction terms of pre-periods and the oil and gas dummy from quarter negative 5 to negative 2 and re-estimate equation (2). Table S7 shows small and not statistically significant estimates on $Pre \times OG$, suggesting these two sectors do not have different trajectories before the policy rollback. In addition, Table S1 serves to confirm that average methane concentrations in pixels with oil and gas infrastructure also showed increases after the August 13 policy rollback. Across a range of regression control specifications, we see that these concentrations indeed increased (by 2.2 ppb, 8.8% of the standard deviations) and this increase is statistically distinguishable from zero.

5.3 Self-reported emissions

Firms may underreport emissions (e.g. Zahran *et al.*, 2014; Shen *et al.*, 2020; Gray and Shimshack, 2011). If the rollback lead to more underreporting, we may detect lower increases in methane emissions in self-reported data, when compared with remotely sensed data. We obtain self-reported methane data from the EPA's Greenhouse Gas Emissions from Large Facilities and re-estimate equation (1). The data are reported at the unit-year level, and each unit is linked to its parent company and sector. We compare oil and gas facilities' methane emissions change in and after 2020, relative to other sectors' changes.

In Table 5 Panel A, negative estimates of the *Post* coefficient suggest all facilities have decreased methane emissions in 2020 compared with that in 2019, potentially due to reduced energy demand during COVID. Relative to this annual difference, oil and gas companies reported 3.8 more metric tons of release per unit-year, or 14.9% relative to the average. Estimates are robust to state and company fixed effects. In Panel B, we add year 2018 and 2021 data as a robustness check. Estimates on $Post \times OG$ show oil and gas facilities have a 16.2% increase in self-reported methane emissions in and after 2020.

Qualitatively, the self-reported data are consistent with the satellite data, insofar as rollback response is concerned. That is, firms "admit" to higher emissions following the policy rollback. The Trump administration amendments indeed lead to significantly increased methane emissions. Turning to the magnitude of this response, ultra-emission events as captured by satellite have a much larger increase than self-reported emissions. There are two potential reasons. First, the most severe leaks captured by the the satellite event data may respond more to the policy than small leaks. Annual, self-reported emissions include both severe and smaller leaks, attenuating impact magnitudes. Second, the tendency to under-report may increase with the policy rollback, particularly as the required frequency of leak monitoring declined.

5.4 Stock market response

An objective of the policy amendment is to reduce the costs of leakage abatement faced by oil and gas companies. If this cost-saving effect is significant in companies' profit profiles, we expect an increase in the stock prices of oil and gas companies after the policy's implementation.[10] To test this hypothesis, we obtain stock price data for publicly listed companies within the S&P 500 and MSCI World. Using the Global Industry Classification Standard (GICS), we focus on three sectors: Oil & Gas Exploration & Production, Coal & Consumable Fuels, and Electric Utilities. In our sample, there were 15, 1, and 41 companies in these sectors, respectively. Table S8 displays the companies and their tickers. We compare the changes in stock prices before and after the policy amendment for the 15 oil and gas companies relative to the changes in the other 42 companies.

Table 6 presents the difference-in-difference estimates.[11] Coefficients on $Post \times OG$ indicate that the policy amendment results in a significant decrease of 0.2 percentage points in oil and gas companies' stock prices. Estimates remain stable with different seasonality and company fixed effects added. Figure 4 displays stock price responses in oil and gas companies and a synthetic control of companies. We observe a reduction of 0.1 percentage points in stock prices after the amendment week in comparison to the control companies' stocks.

Given the nimble response of asset vauations, we use a shorter time window as a robustness check to mitigate potential confounders that could also affect oil and gas companies' stock prices. In Table S9 Column (1) and (2), we re-run our analysis using a sample from two weeks before to two weeks after the policy date, August 13, 2020. Estimates on $Post \times OG$ are close to zero and not statistically significant, suggesting no differential changes faced by oil and gas companies compared to other S&P stocks. We also use an alternative event date, September 24, 2019, to assign $Post$ and construct

[10]We consider the policy announcement surprising during our study period. According to EPA (2022), there were discussions about policy amendments in March 2018, but no further action was taken until August 2020. Figure S2 shows that there was little change in online search interest for the word "methane" or "natural gas" around August 2020.

[11]To account for the level difference in stock price, we use normalized close price as the dependent variable. The normalized price is defined as the unadjusted close price relative to the 2018 baseline price. Normalized price = (Unadjusted close price - base price) / base price. Base price is the average close price in the year 2018.

the analysis sample. On this day, the EPA released a proposed rule that mentioned the relaxation of methane requirements, though it was not in effect until August 2020. Column (3) and (4) show negative and significant estimates on $Post \times OG$, similar to those in Table 6. This suggests the announcement of the proposed rollback did not lead to an increase in stock prices or perceived profitability from investors.

These results show little evidence that the policy amendment reduces companies' costs and increases profits. One possible explanation is that removing the monitoring requirement has no meaningful impact on the costs of leak reductions. It is possible that methane slip control facilities have already been installed at high fixed costs with low marginal costs of operation. As a result, the policy amendment has negligible effects on the total cost. Leak abatement costs may also be negligible from investors' perspective, and stock prices are thereby not affected by changes in leak/venting activities, despite these activities having large impacts on ambient methane concentrations.

5.5 Natural gas market

Dynamics in the natural gas market could confound our estimates. Methane leakages result in economic losses, and fossil fuel companies have stronger incentives to control leaks when natural gas prices are higher (Hausman and Muehlenbachs, 2019; Lade and Rudik, 2020). Given the fluctuation in natural gas prices in 2020, the observed increase in methane emissions after August 2020 might be influenced by the natural gas market rather than the policy rollback.

To address this concern, we obtain natural gas price, drilling, consumption, and production data from the EIA. The monthly figures in Figure S3 display fluctuations in natural gas production and consumption in both 2019 and 2020. There was a significant reduction in drilling activities following the COVID outbreak, with a rebound observed after May 2020. Natural gas prices also dropped in early 2020 and gradually increased by mid-2020. However, none of these fluctuations in the natural gas market coincided with the timing of our policy change of interest in August 2020. This suggests that the observed spike in ultra-emission of methane is unlikely to be driven by changes in the natural gas market.

5.6 Environmental enforcement

Environmental enforcement changed in 2020 during and after the COVID pandemic. Observing fewer inspections, fossil fuel companies may exert lower efforts in leakage reduction. Therefore, it may be the COVID-induced enforcement change rather than the policy amendment that drives our results. If the oil and gas sector received extra relaxation in environmental enforcement compared to other sectors (including coal), we could still estimate positive coefficients in Table 3 and Figure 3. To address the potential confounding effect of environmental enforcement changes, in this section, we test whether the oil and gas sectors experienced a change using data from the ICIS-AIR, which contains compliance and permit data for stationary sources of air and greenhouse gas emissions regulated by the EPA, state, and local air pollution agencies. We focus on inspection data at the event level. For each inspection, we observe the inspection time, facility identifier, name, violation, and action. We consider facilities whose names include “gas”, “oil”, “petrol”, or “energy” as treated facilities in the oil and gas sector, and other facilities as control ones. This practice results in 5,846 oil and gas facilities and 52,493 other facilities.

We test environmental enforcement responses to the COVID outbreak and policy amendment using a difference-in-difference design. Our outcome variable is the number of inspections received by each facility-week, with oil and gas considered as treated and other sectors as controls. In Table S10, Panel A shows that after the COVID outbreak, the number of inspections decreased for all industries, as indicated by negative coefficients on *PostCOVID*. However, inspections received by the oil and gas sector decreased the least, captured in the positive estimates on *PostCOVID* $\times$ *Treated*. This addresses the confounding concern and suggests that the driving force behind our findings is not solely due to the extra environmental relaxation induced by the COVID outbreak in the oil and gas sector.

After the policy amendment, estimates on *PostRollback* $\times$ *Treated* indicate that environmental relaxation in the oil and gas sector is stronger compared to other sectors. Specifically, each oil and gas facility receives 0.004 fewer inspections per week, or 24.3% relative to the average inspection count. This suggests that our observed methane increase could be attributed to the environmental enforcement channel. In Table S10 Panel B, we use an alternative definition for oil and gas facilities by linking facility identifiers with methane emissions' stack test results to identify high methane-emitting facilities. Estimates on *PostCOVID* $\times$ *Treated* remain positive, and estimates on *PostRollback* $\times$ *Treated* are negative and precise, confirming that the COVID outbreak did not lead to different enforcement faced by oil and gas sectors, but rather the policy amendment decreased enforcement faced by the oil and gas sector.

6 Discussion

Across three data sources, methane emissions increased significantly at oil and gas infrastructure sites following the 2020 rollback of US methane emissions policy. The industry response was nimble and generated a substantial environmental externality.

“Super-emitter” methane events are receiving increasing attention from policymakers and the press due to radically improved detection by satellites. We find the 2020 federal rollback lead to an increase in of ultra-emission events by 124%. Assuming maximum facility operation (24-hour), the policy relaxation lead the oil and gas sector methane emissions to increase by 221.8 tons per day, based on the average detected flow rate of 80,957 tons per year. This is equivalent to 0.87% of the total methane emissions from this sector (U.S. Environmental Protection Agency, 2023). To offset the warming induced by the rollback, roughly 92 million more trees would need to be planted.[12,13] Our large climate impact estimate underscores the importance of ultra-emission events, and more auspiciously, how quickly they respond to policy.

[12]According to European Environment Agency (2012), an average tree takes up about 22 kilograms of carbon dioxide from the atmosphere.

[13]“One-off” planting, not per year.

The oil and gas sector routinely argues that it is in its own economic interest to reduce methane emissions. For example, ExxonMobil highlights its methane leak detection program, stating:

> *As a company in the business of selling natural gas, we also want to minimize waste of that natural resource for ourselves and our resource owners. It is in our economic interest to ensure our product is captured in the pipe and sold to consumers.*[14]

This industry argument ignores the fact that reducing emissions is costly to firms. Without government intervention, firms will only reduce emissions to the point where the marginal abatement effort matches their private economic return to abatement: the amount for which they can sell the abated gas. Implicitly, the US Methane rule caused firms to value methane emissions beyond this private financial return and closer to the societal benefit. Critically, this societal benefit is large given methane's large and growing contribution to climate change.

[14]Source: https://www.ishn.com/articles/110411-exxonmobil-considers-aerial-methane-gas-monitoring

References

Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., and Hamburg, S. P. (2012). Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences*, **109**(17), 6435–6440.

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Shepson, P. B., Sweeney, C., Townsend-Small, A., Wofsy, S. C., and Hamburg, S. P. (2018). Assessment of methane emissions from the u.s. oil and gas supply chain. *Science*, **361**(6398), 186–188.

Chen, Y., Sherwin, E. D., Berman, E. S., Jones, B. B., Gordon, M. P., Wetherley, E. B., Kort, E. A., and Brandt, A. R. (2022). Quantifying regional methane emissions in the new mexico permian basin with a comprehensive aerial survey. *Environmental Science & Technology*, **56**(7), 4317–4323.

de Gouw, J., Veefkind, J., Roosenbrand, E., Dix, B., Lin, J., Landgraf, J., and Levelt, P. (2020). Daily satellite observations of methane from oil and gas production regions in the united states. *Scientific Reports*, **10**.

EPA (2022). Actions and notices about oil and natural gas air pollution standards.

Errickson, F. C., Keller, K., Collins, W. D., Srikrishnan, V., and Anthoff, D. (2021). Equity is more important for the social cost of methane than climate uncertainty. *Nature*, **592**(7855), 564–570.

Etminan, M., Myhre, G., Highwood, E., and Shine, K. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43**(24), 12–614.

European Environment Agency (2012). Trees help tackle climate change.

Gray, W. B. and Shimshack, J. P. (2011). The effectiveness of environmental monitoring and enforcement: A review of the empirical evidence. *Review of Environmental Economics and Policy*.

Hausman, C. and Muehlenbachs, L. (2019). Price regulation and environmental externalities: Evidence from methane leaks. *Journal of the Association of Environmental and Resource Economists*, **6**(1), 73–109.

Howarth, R. W. (2022). Methane emissions from the production and use of natural gas. *The Magazine for Environmental Managers*.

Hu, H., Landgraf, J., Detmers, R., Borsdorff, T., Aan de Brugh, J., Aben, I., Butz, A., and Hasekamp, O. (2018). Toward global mapping of methane with tropomi: First results and intersatellite comparison to gosat. *Geophysical Research Letters*, **45**(8), 3682–3689.

Irakulis-Loitxate, I., Guanter, L., Liu, Y.-N., Varon, D., Maasakkers, J., Zhang, Y., Chulakadabba, A., Wofsy, S., Thorpe, A., Duren, R., Frankenberg, C., Lyon, D., Hmiel, B., Cusworth, D., Zhang, Y., Segl, K., GorroÃ±o, J., SÃ¡nchez-GarcÃa, E., Sulprizio, M., and Jacob, D. (2021). Satellite-based survey of extreme methane emissions in the permian basin. *Science Advances*, **7**, eabf4507.

Irakulis-Loitxate, I., Guanter, L., Maasakkers, J., Zavala-Araiza, D., and Aben, I. (2022). Satellites detect abatable super-emissions in one of the world's largest methane hotspot regions. *Environmental science & technology*, **56**.

Jackson, R. B., Saunois, M., Bousquet, P., Canadell, J. G., Poulter, B., Stavert, A. R., Bergamaschi, P., Niwa, Y., Segers, A., and Tsuruta, A. (2020). Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environmental Research Letters*, **15**(7), 071002.

Ladage, S., Blumenberg, M., Franke, D., Bahr, A., Lutz, R., and Schmidt, S. (2021). On the climate benefit of a coal-to-gas shift in germany's electric power sector. *Scientific reports*, **11**(1), 11453.

Lade, G. E. and Rudik, I. (2020). Costs of inefficient regulation: Evidence from the bakken. *Journal of Environmental Economics and Management*, **102**, 102336.

Lauvaux, T., Giron, C., Mazzolini, M., daAspremont, A., Duren, R., Cusworth, D., Shindell, D., and Ciais, P. (2022). Global assessment of oil and gas methane ultra-emitters. *Science*, **375**(6580), 557–561.

Mohlin, K., Lackner, M., Nguyen, H., and Wolfe, A. (2022). Mohlin, kristina and lackner, maureen and nguyen, huong and wolfe, aaron, policy instrument options for addressing methane emissions from the oil and gas sector. Technical report, EDF Economics Discussion Paper Series 22 – 01.

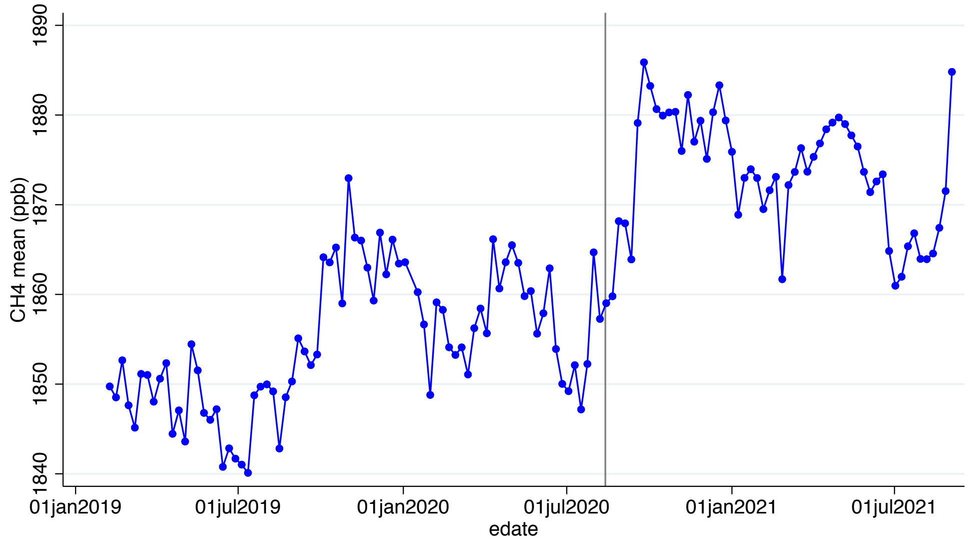
Shen, P., Betz, R., Ortmann, A., and Gong, R. (2020). Improving truthful reporting of polluting firms by rotating inspectors: Experimental evidence from a bribery game. *Environmental and Resource Economics*, **76**, 201–233.

Stein, A., Draxler, R. R., Rolph, G. D., Stunder, B. J., Cohen, M., and Ngan, F. (2015). Noaa's hysplit atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society*, **96**(12), 2059–2077.

U.S. Environmental Protection Agency (2023). Greenhouse gas inventory data explorer.

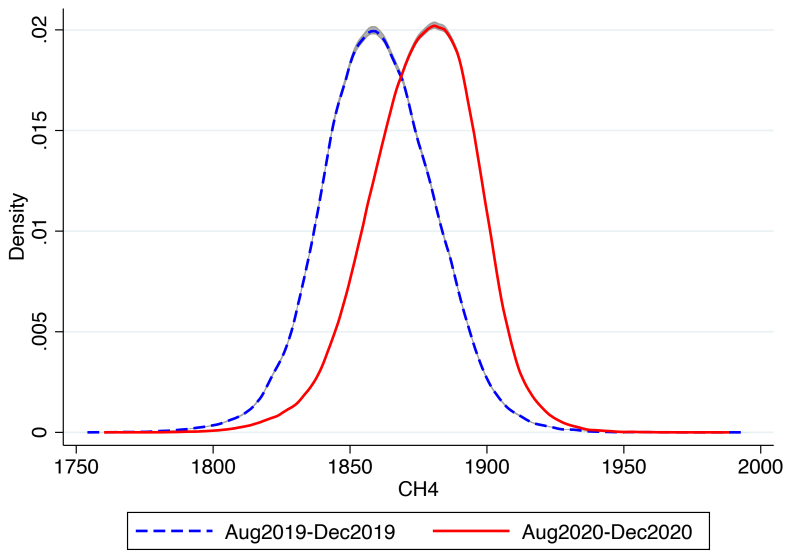
Zahran, S., Iverson, T., Weiler, S., and Underwood, A. (2014). Evidence that the accuracy of self-reported lead emissions data improved: A puzzle and discussion. *Journal of Risk and Uncertainty*, **49**, 235–257.

Figure 1: Methane in pixels with natural gas facilities



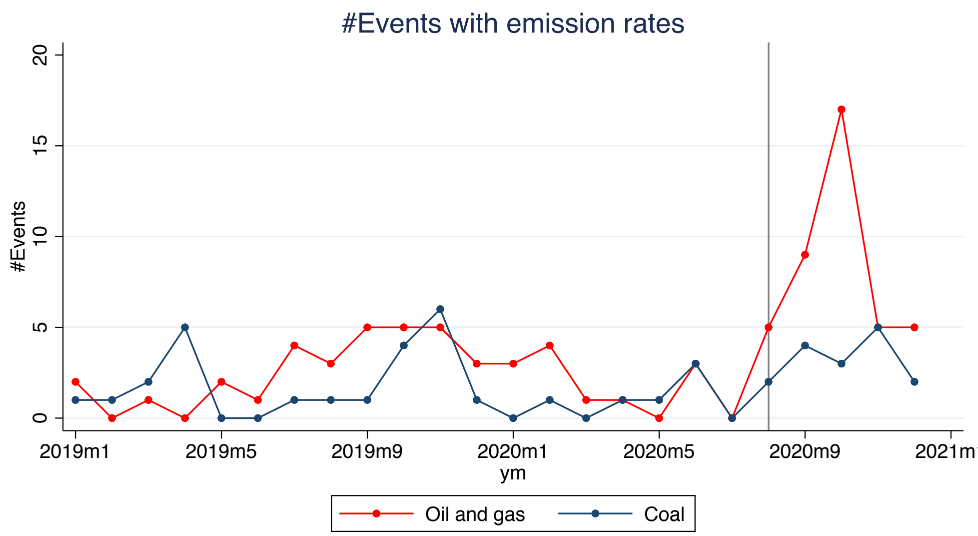
Notes: 0.1-degree sample pixels have at least one drilling well, processing plant, distribution pipeline, or compressor station inside. Methane data is aggregated to the weekly level from TROPOMI daily product Feb 8, 2019 - Sep 3, 2021.

Figure 2: Distribution of methane concentration in 2019 and 2020



Notes: This figure displays kernel density histograms for ambient methane in treated pixels. The red curve shows the methane distribution before the policy rollback. The blue curve shows the distribution during the same periods in 2019. Gray bars are 95% confidence intervals.

Figure 3: #Emission events with emission rates



Notes: Emission events without emission rates are mostly clustered in the Permian Basin and are hard to estimate flows.

Table 1: Methane in pixels with and without leak sites

	CH$_4$ (ppb)					
	(1)	(2)	(3)	(4)	(5)	(6)
Event pixel	22.304***	17.305***	17.681***	17.737***	17.806***	17.857***
	(1.664)	(1.326)	(1.353)	(1.357)	(1.356)	(1.360)
Observations	2578039	2578039	2578039	2578039	2578039	2578039
R-squared	0.005	0.125	0.385	0.410	0.430	0.463
Y-mean treated	1885.435	1885.435	1885.435	1885.435	1885.435	1885.435
Y-sd treated	24.908	24.908	24.908	24.908	24.908	24.908
Y-mean control	1863.131	1863.131	1863.131	1863.131	1863.131	1863.131
Y-sd control	20.225	20.225	20.225	20.225	20.225	20.225
Year FEs			Y	Y	Y	Y
Quarter FEs			Y			
State*Quarter FEs				Y		
Month FEs					Y	
State*Month FEs						Y
State FEs		Y	Y		Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Event pixel* is one if the pixel includes at least one emission event Jan 2019 - Dec 2020 regardless of sector. Pixels are required to have at least half non-missing CH$_4$ data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table 2: Methane in pixels with natural gas facilities

	CH_4 (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	14.703***	10.516***	10.037***	2.825***	2.648***
	(0.055)	(0.073)	(0.072)	(0.092)	(0.092)
Y2020	8.786***				
	(0.040)				
Post × Y2020	5.032***	5.234***	5.348***	4.439***	4.618***
	(0.060)	(0.056)	(0.053)	(0.055)	(0.054)
Observations	797790	797790	797790	797790	797790
R-squared	0.570	0.612	0.637	0.630	0.663
Y-mean	1862.163	1862.163	1862.163	1862.163	1862.163
Y-sd	20.116	20.116	20.116	20.116	20.116
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between Aug 13, 2019 - Dec 31, 2019 or between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH_4 data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table 3: Major emission events with emission rate

	#Emission events				
	(1)	(2)	(3)	(4)	(5)
Post	0.063**	0.025	0.038	-0.002	0.016
	(0.031)	(0.037)	(0.039)	(0.039)	(0.042)
Post × OG	0.148***	0.148***	0.121**	0.148***	0.112**
	(0.043)	(0.043)	(0.050)	(0.043)	(0.053)
OG	0.027	0.027		0.027	
	(0.018)	(0.018)		(0.018)	
Observations	1438	1438	1438	1438	1438
R-squared	0.042	0.058	0.060	0.067	0.078
Y-mean	0.090	0.090	0.090	0.090	0.090
Y-sd	0.322	0.322	0.322	0.322	0.322
Year FEs		Y	Y	Y	Y
DOW FEs		Y	Y	Y	Y
Quarter FEs		Y			
Sector*Quarter FEs			Y		
Month FEs				Y	
Sector*Month FEs					Y

Notes: Sample includes emission events at the sector-day level, oil and gas (OG) and coal, January 4, 2019 - December 22, 2020.

Table 4: Methane in pixels with natural gas facilities, top 5% leaky pixels

	CH_4 (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	17.319***	12.358***	12.344***	5.347***	4.784***
	(0.197)	(0.341)	(0.346)	(0.606)	(0.603)
Y2020	6.865***				
	(0.180)				
Post × Y2020	6.490***	6.944***	7.008***	5.872***	6.058***
	(0.259)	(0.247)	(0.246)	(0.262)	(0.263)
Observations	42438	42438	42438	42438	42438
R-squared	0.461	0.487	0.496	0.515	0.535
Y-mean	1887.843	1887.843	1887.843	1887.843	1887.843
Y-sd	19.782	19.782	19.782	19.782	19.782
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Instead of using all pixels with natural gas facilities, we use the leakiest pixels that have the 5% highest CH_4 between Feb 8, 2019 - Aug 13, 2020. Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between Aug 13, 2019 - Dec 31, 2019 or between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH_4 data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table 5: Self-reported methane emission

	CH_4 (metric tons)		
	Panel A: 2019-2020		
Post	-4.150***	-4.150***	-4.150***
	(0.601)	(0.602)	(0.602)
Post × OG	3.753***	3.753***	3.753***
	(0.613)	(0.614)	(0.614)
OG	-24.340***	-28.852***	
	(2.169)	(3.004)	
Observations	11418	11418	11418
R-squared	0.008	0.023	0.976
Y-mean	22.874	22.874	22.874
Y-sd	110.716	110.716	110.716
	Panel B: 2018-2021		
Post	-4.522***	-4.522***	-4.522***
	(0.597)	(0.598)	(0.598)
Post × OG	4.076***	4.076***	4.076***
	(0.609)	(0.610)	(0.610)
OG	-26.027***	-30.620***	
	(2.374)	(3.231)	
Observations	21484	21484	21484
R-squared	0.007	0.023	0.969
Y-mean	25.148	25.148	25.148
Y-sd	120.012	120.012	120.012
State FEs		Y	Y
Company FEs			Y

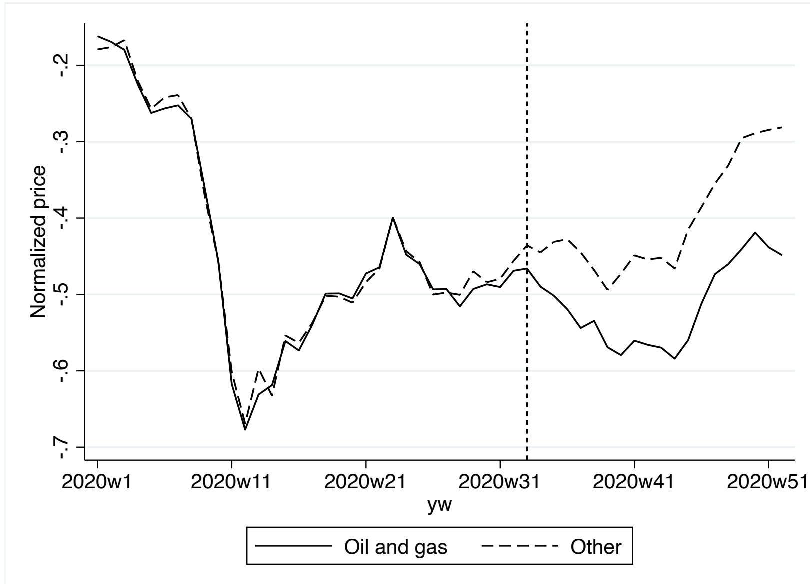
Notes: Sample is at the facility-year level. *Post* is one if the year is in and after 2020 and zero otherwise. Facilities are required to have data every year.

Table 6: Stock price responses

	Normalized close price			
	(1)	(2)	(3)	(4)
Post	0.038	0.039	0.037	0.037
	(0.036)	(0.032)	(0.032)	(0.032)
Post × OG	-0.225***	-0.225***	-0.215***	-0.214***
	(0.057)	(0.058)	(0.064)	(0.064)
OG	-0.368***	-0.368***		
	(0.056)	(0.056)		
Observations	27708	27708	27708	27708
R-squared	0.281	0.295	0.298	0.791
Y-mean	0.050	0.050	0.050	0.050
Y-sd	0.347	0.347	0.347	0.347
Year FEs		Y	Y	
DOW FEs		Y	Y	Y
Month FEs		Y		
Group*Month FEs			Y	Y
Company FEs				Y

Notes: Sample includes normalized close price at the company-day level, 15 S&P500 oil and gas companies and 42 coal and electric utilities companies, January 1, 2019 - December 31, 2020. *OG* is a binary classification, oil & gas or other company. Standard errors are clustered at the company level.

Figure 4: Stock price responses, synthetic control



Notes: This figure shows stock price at the sector-week level for oil and gas sector, and synthetic control companies in coal and electric utility sector in 2020. We use pre-policy stock price to calculate weights in the donor pool.

Online Appendix

Table S1: Methane in pixels with leak sites

	CH$_4$ (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	14.942***	8.744***	9.671***	4.641***	5.862***
	(0.993)	(1.122)	(1.016)	(1.038)	(0.977)
Post × OG	4.227***	3.967***	3.135***	3.170***	2.167**
	(1.019)	(1.056)	(0.936)	(1.006)	(0.923)
Observations	15619	15619	15619	15619	15619
R-squared	0.585	0.641	0.650	0.667	0.684
Y-mean	1886.325	1886.325	1886.325	1886.325	1886.325
Y-sd	24.744	24.744	24.744	24.744	24.744
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample pixels include coordinates experiencing at least one high emission events Jan 2019 - Aug 2020. Pixels are required to have at least half non-missing CH$_4$ data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table S2: Single difference analysis

	CH_4 (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	21.006***	9.702***	9.566***	4.860***	5.017***
	(0.049)	(0.056)	(0.055)	(0.053)	(0.052)
Observations	797790	797790	797790	797790	797790
R-square	0.510	0.599	0.625	0.630	0.663
Y-mean	1862.163	1862.163	1862.163	1862.163	1862.163
Y-sd	20.116	20.116	20.116	20.116	20.116
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH_4 data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table S3: Methane in pixels with natural gas facilities

	CH$_4$ (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	15.740***	11.607***	11.082***	3.694***	3.480***
	(0.055)	(0.074)	(0.073)	(0.092)	(0.092)
Y2020	9.652***				
	(0.041)				
Post × Y2020 × Well	2.122***	2.276***	2.240***	1.850***	1.851***
	(0.079)	(0.078)	(0.070)	(0.077)	(0.068)
Post × Y2020 × Processing	-1.354***	-1.456***	-1.360***	-1.298***	-1.247***
	(0.349)	(0.343)	(0.301)	(0.332)	(0.289)
Post × Y2020 × Pipeline	2.63***	2.71***	2.99***	2.2***	2.55***
	(.0761)	(.0749)	(.0669)	(.0733)	(.0646)
Post × Y2020 × Compressor	-.443	-.362	.0644	-.431	.101
	(.284)	(.287)	(.233)	(.282)	(.219)
Observations	797790	797790	797790	797790	797790
R-squared	0.568	0.610	0.635	0.629	0.662
Y-mean	1862.163	1862.163	1862.163	1862.163	1862.163
Y-sd	20.116	20.116	20.116	20.116	20.116
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between Aug 13, 2019 - Dec 31, 2019 or between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH$_4$ data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table S4: Heterogeneity across facilities

	Panel A: Storage and transmission facilities				
	CH$_4$ (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	14.467***	10.412***	9.909***	2.517***	2.289***
	(0.065)	(0.088)	(0.088)	(0.112)	(0.112)
Y2020	8.519***				
	(0.046)				
Post × Y2020	5.133***	5.360***	5.448***	4.661***	4.788***
	(0.071)	(0.065)	(0.062)	(0.064)	(0.063)
Observations	592283	592283	592283	592283	592283
R-squared	0.569	0.613	0.640	0.630	0.667
Y-mean	1862.758	1862.758	1862.758	1862.758	1862.758
Y-sd	20.317	20.317	20.317	20.317	20.317
	Panel B: Other facilities				
Post	15.400***	10.871***	10.406***	3.710***	3.716***
	(0.101)	(0.128)	(0.125)	(0.152)	(0.153)
Y2020	9.567***				
	(0.081)				
Post × Y2020	4.728***	4.871***	5.000***	3.808***	4.032***
	(0.113)	(0.107)	(0.103)	(0.106)	(0.104)
Observations	205507	205507	205507	205507	205507
R-squared	0.569	0.607	0.631	0.626	0.659
Y-mean	1860.448	1860.448	1860.448	1860.448	1860.448
Y-sd	19.424	19.424	19.424	19.424	19.424
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between Aug 13, 2019 - Dec 31, 2019 or between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH$_4$ data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table S5: Triple difference

	CH$_4$ (ppb)				
	(1)	(2)	(3)	(4)	(5)
Post	15.400***	11.292***	10.351***	3.650***	3.006***
	(0.101)	(0.108)	(0.102)	(0.120)	(0.115)
Y2020	9.567***				
	(0.081)				
Post × Y2020	4.728***	4.892***	4.998***	3.998***	4.176***
	(0.113)	(0.108)	(0.105)	(0.107)	(0.104)
Post × Facility	-.933***	-1.05***	-.42***	-1.12***	-.478***
	(.12)	(.113)	(.1)	(.111)	(.0993)
Y2020 × Facility	-1.05***	-1.09***	-1.2***	-1.13***	-1.19***
	(.0931)	(.0931)	(.0926)	(.0933)	(.0918)
Post × Y2020 × Facility	.404***	.455***	.471***	.589***	.597***
	(.133)	(.127)	(.123)	(.126)	(.122)
Observations	797790	797790	797790	797790	797790
R-squared	0.570	0.612	0.637	0.630	0.663
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Single term *Facility* is absorbed by pixel FEs. Standard errors are clustered at the pixel level.

Table S6: Methane in pixels with natural gas facilities

	CH_4 (ppb)				
	Panel A: Drop pixels with landfill facilities				
	(1)	(2)	(3)	(4)	(5)
Post	14.804***	10.556***	10.108***	2.963***	2.804***
	(0.056)	(0.075)	(0.074)	(0.094)	(0.095)
Y2020	8.816***				
	(0.041)				
Post × Y2020	4.990***	5.217***	5.331***	4.414***	4.593***
	(0.062)	(0.057)	(0.055)	(0.056)	(0.055)
Observations	746899	746899	746899	746899	746899
R-squared	0.571	0.613	0.637	0.631	0.663
Y-mean	1862.344	1862.344	1862.344	1862.344	1862.344
Y-sd	20.139	20.139	20.139	20.139	20.139
	Panel B: Drop counties in the top quartile of CAFO intensity				
Post	15.112***	10.731***	10.202***	3.103***	2.930***
	(0.062)	(0.083)	(0.083)	(0.105)	(0.106)
Y2020	9.029***				
	(0.046)				
Post × Y2020	4.456***	4.756***	4.971***	3.985***	4.232***
	(0.065)	(0.061)	(0.060)	(0.061)	(0.061)
Observations	613092	613092	613092	613092	613092
R-squared	0.578	0.615	0.638	0.632	0.663
Y-mean	1861.936	1861.936	1861.936	1861.936	1861.936
Y-sd	20.101	20.101	20.101	20.101	20.101
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
State*Quarter FEs			Y		
Month FEs				Y	
State*Month FEs					Y
Pixel FEs	Y	Y	Y	Y	Y

Notes: Sample is at the pixel-week level Feb 8, 2019 - Dec 31, 2020. *Post* is one if the week is between Aug 13, 2019 - Dec 31, 2019 or between Aug 13, 2020 - Dec 31, 2020. Pixels are required to have at least half non-missing CH_4 data in the pre- and post-period. There are 78 weeks in the pre-period and 57 weeks in the post-period, so pixels have at least 39 and 29 obs in the pre- and post-period. Standard errors are clustered at the pixel level.

Table S7: Major emission events with emission rate, pre-trend test

	#Emission events				
	(1)	(2)	(3)	(4)	(5)
Pre Q5 $\times$ OG	-0.019	-0.019	-0.078	-0.019	-0.169
	(0.061)	(0.061)	(0.131)	(0.061)	(0.200)
Pre Q4 $\times$ OG	0.001	0.001	0.007	0.001	0.016
	(0.056)	(0.056)	(0.056)	(0.055)	(0.057)
Pre Q3 $\times$ OG	0.042	0.042	-0.010	0.042	-0.140
	(0.056)	(0.056)	(0.075)	(0.055)	(0.140)
Pre Q2 $\times$ OG	0.066	0.066	0.010	0.066	-0.082
	(0.056)	(0.056)	(0.113)	(0.055)	(0.189)
Post	.0701*	.0191	.0444	-.112	-.0225
	(.0387)	(.0473)	(.0547)	(.0767)	(.101)
Post $\times$ OG	.168***	.168***	.118	.168***	-.0103
	(.0547)	(.0545)	(.0773)	(.0544)	(.143)
OG	.00741	.00741		.00741	
	(.0384)	(.0383)		(.0382)	
Observations	1438	1438	1438	1438	1438
R-squared	0.051	0.063	0.064	0.071	0.082
Y-mean	0.090	0.090	0.090	0.090	0.090
Y-sd	0.322	0.322	0.322	0.322	0.322
Year FEs		Y	Y	Y	Y
DOW FEs		Y	Y	Y	Y
Quarter FEs		Y			
Sector*Quarter FEs			Y		
Month FEs				Y	
Sector*Month FEs					Y

Notes: Sample includes emission events at the sector-day level, oil and gas (OG) and coal, January 4, 2019 - December 22, 2020.

Table S8: List of companies within S&P 500 and MSCI World

Company Name	Ticker	Sector
Aker Bo Asa	AKRBP	Oil & Gas Exploration & Production
Apache Corp	APA	Oil & Gas Exploration & Production
Conocophillips	COP	Oil & Gas Exploration & Production
Coterra Enercoterra Energy inc	CTRA	Oil & Gas Exploration & Production
Devon Energy	DVN	Oil & Gas Exploration & Production
Eog Resources	EOG	Oil & Gas Exploration & Production
Diamondback Energy Inc	FANG	Oil & Gas Exploration & Production
Hess Corporation	HES	Oil & Gas Exploration & Production
Inpex Corp	INPEX	Oil & Gas Exploration & Production
Lundin Energy Ab	LUNE	Oil & Gas Exploration & Production
Marathon Oil Corp	MRO	Oil & Gas Exploration & Production
Pioneer Natural Resources	PXD	Oil & Gas Exploration & Production
Santos Ltd	STO	Oil & Gas Exploration & Production
Tourmaline Oil	TOU	Oil & Gas Exploration & Production
Woodside Petroleum Ltd	WPL	Oil & Gas Exploration & Production
Washington H. Soul Pattinson	SOL	Coal & Consumable Fuels
Clp Holdings Ltd.	2	Electric Utilities
Power Assets Holdings Ltd.	6	Electric Utilities
Enel Spa	441	Electric Utilities
Ck Infrastructure Holdings Ltd.	1038	Electric Utilities
Hk Electric Investments And Hk Electric Investme	2638	Electric Utilities
Sse PIc	4208	Electric Utilities
Tokyo Electric Power Company Holdings Inc	9501	Electric Utilities
Chub Electric Power Co Inc	9502	Electric Utilities
The Kansai Electric Power Co Inc	9503	Electric Utilities
Fortum Ovi	24271	Electric Utilities
Rsted	122544	Electric Utilities
Terna	290022	Electric Utilities
Elia System Op.	1110103	Electric Utilities
Edf	1110855	Electric Utilities
Energias De Portugal	1111424	Electric Utilities
American Electric Power Company	AEP	Electric Utilities
Constellation Energy - W/I	CEGVV	Electric Utilities
Duke Energy Corp	DUK	Electric Utilities
Edison Intl	EIX	Electric Utilities
Endesa,S.A.	ELE	Electric Utilities
Emera Inc	EMA	Electric Utilities
Eversource Energy	ES	Electric Utilities
Entergy Corporation	ETR	Electric Utilities
Evergy Inc	EVRG	Electric Utilities
Exelon Corp	EXC	Electric Utilities
Firstenergy Corp	FE	Electric Utilities
Fortis	FTS	Electric Utilities
Hydro One Ltd	H	Electric Utilities
Acciones Iberdrola	IBE	Electric Utilities

Alliant Energy Corp	LNT	Electric Utilities
Mercury Nz Ltd	MCY	Electric Utilities
Nextera Energy Inc	NEE	Electric Utilities
Nrg Energy Inc	NRG	Electric Utilities
Verbund Ag	OEZVY	Electric Utilities
Origin Energy Ltd	ORG	Electric Utilities
Pg&E Corp	PCG	Electric Utilities
Pinnacl West Cap	PNW	Electric Utilities
Ppl Corp	PPL	Electric Utilities
Red Electrica Corporacion, S.A.	REE	Electric Utilities
Southern Co	SO	Electric Utilities
Xcel Energy Inc	XEL	Electric Utilities

Table S9: Stock price responses

	Normalized close price			
	(1)	(2)	(3)	(4)
Post	-0.011**	-0.008	0.011*	0.011**
	(0.005)	(0.005)	(0.006)	(0.004)
Post × OG	0.018	0.010	-0.067***	-0.067***
	(0.011)	(0.010)	(0.009)	(0.008)
OG	-0.549***	0.000	-0.344***	0.000
	(0.088)	(.)	(0.064)	(.)
Observations	1149	1149	1140	1140
R-square	0.304	0.996	0.313	0.993
Y-mean	0.013	0.013	0.101	0.101
Y-sd	0.426	0.426	0.298	0.298
Company FEs		Y		Y

Notes: Sample includes normalized close price at the company-day level, 15 S&P500 oil and gas companies and 42 coal and electric utilities companies. *OG* is a binary classification, oil & gas or other company. In Column (1) and (2), sample includes 2 weeks before to 2 weeks after August 13, 2020. In Column (3) and (4), sample includes 2 weeks before to 2 weeks after September 24, 2020. Standard errors are clustered at the company level.

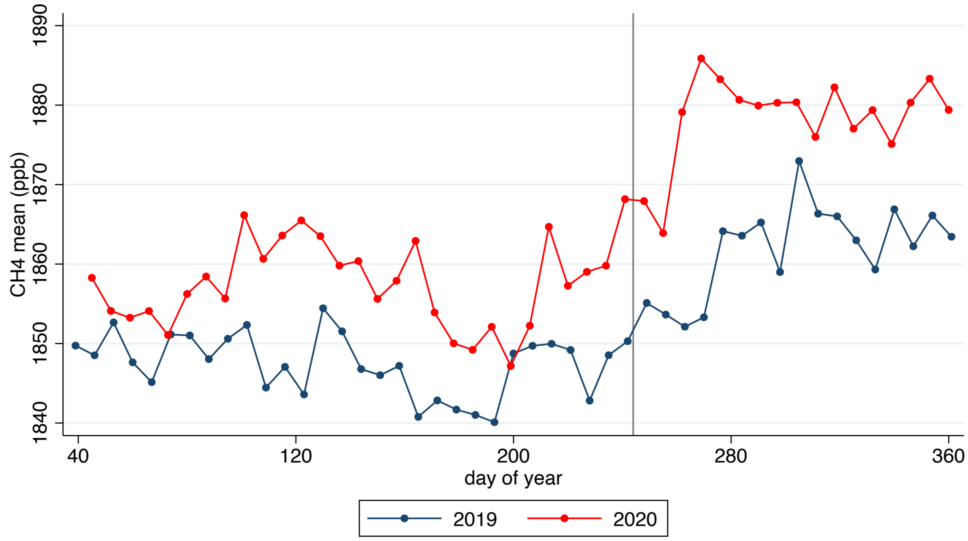
Table S10: Environmental enforcement responses to the COVID and policy roll-back

	Panel A: Name matches				
	#Inspection				
PostCOVID	-3.6189***	-6.7890***	-6.8436***	-5.3364***	-5.4643***
	(0.1596)	(0.3012)	(0.3010)	(0.3335)	(0.3353)
PostCOVID × Treated	1.0550**	1.0550**	1.5998**	1.0550**	2.3309***
	(0.5284)	(0.5284)	(0.6437)	(0.5284)	(0.6439)
PostRollback	0.6881***	2.6591***	2.6536***	3.2765***	3.4534***
	(0.1939)	(0.2386)	(0.2415)	(0.2539)	(0.2558)
PostRollback × Treated	-2.0854***	-2.0854***	-2.0300**	-2.0854***	-3.8515***
	(0.7938)	(0.7938)	(1.0057)	(0.7938)	(1.2069)
Treated	1.796***	1.796***		1.796***	
	(.6594)	(.6594)		(.6594)	
Observations	6067256	6067256	6067256	6067256	6067256
R-squared	0.0001	0.0008	0.0008	0.0016	0.0017
Y-mean	15.8403	15.8403	15.8403	15.8403	15.8403
Y-sd	155.6107	155.6107	155.6107	155.6107	155.6107
	Panel B: High methane emitters				
PostCOVID	-3.6189***	-7.0284***	-7.0232***	-5.6820***	-5.6948***
	(0.1596)	(0.3028)	(0.3028)	(0.3404)	(0.3406)
PostCOVID × Treated	0.5957	0.5957	0.1575	0.5957	1.6751
	(0.9714)	(0.9714)	(1.0558)	(0.9714)	(1.1332)
PostRollback	0.6881***	2.6210***	2.6393***	3.3859***	3.4534***
	(0.1939)	(0.2411)	(0.2417)	(0.2548)	(0.2558)
PostRollback × Treated	-0.3208	-0.3208	-1.8646	-0.3208	-6.0035***
	(1.2396)	(1.2396)	(1.5204)	(1.2396)	(1.6905)
Treated	-5.536***	-5.536***		-5.536***	
	(.5989)	(.5989)		(.5989)	
Observations	5524896	5524896	5524896	5524896	5524896
R-squared	0.0001	0.0009	0.0009	0.0017	0.0017
Y-mean	15.5941	15.5941	15.5941	15.5941	15.5941
Y-sd	152.7799	152.7799	152.7799	152.7799	152.7799
Year FEs		Y	Y	Y	Y
Quarter FEs		Y			
Treated*Quarter FEs			Y		
Week FEs				Y	
Treated*Week FEs					Y

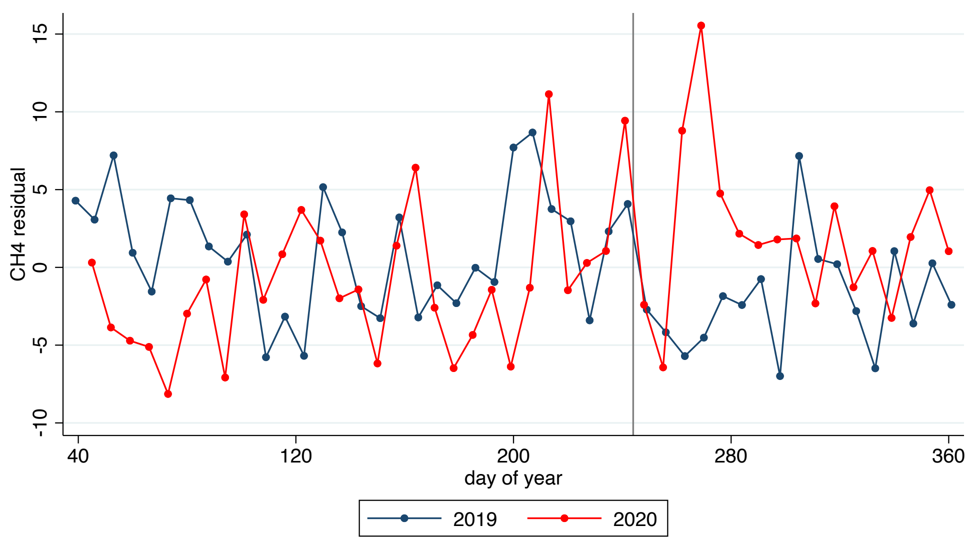
Notes: Sample includes inspection events at the facility-week level 2019-2020. Outcome variable is multiplied by 1000. Standard errors are clustered at the facility level.

Figure S1: Methane in pixels with natural gas facilities, 2019 vs. 2020

Panel A: Raw data

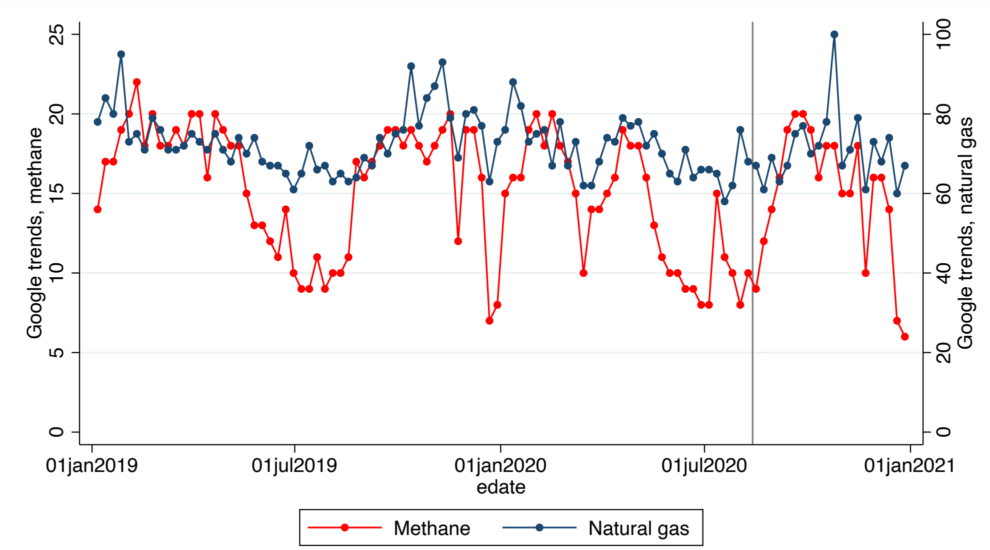


Panel B: Residuals with year and month fixed effects



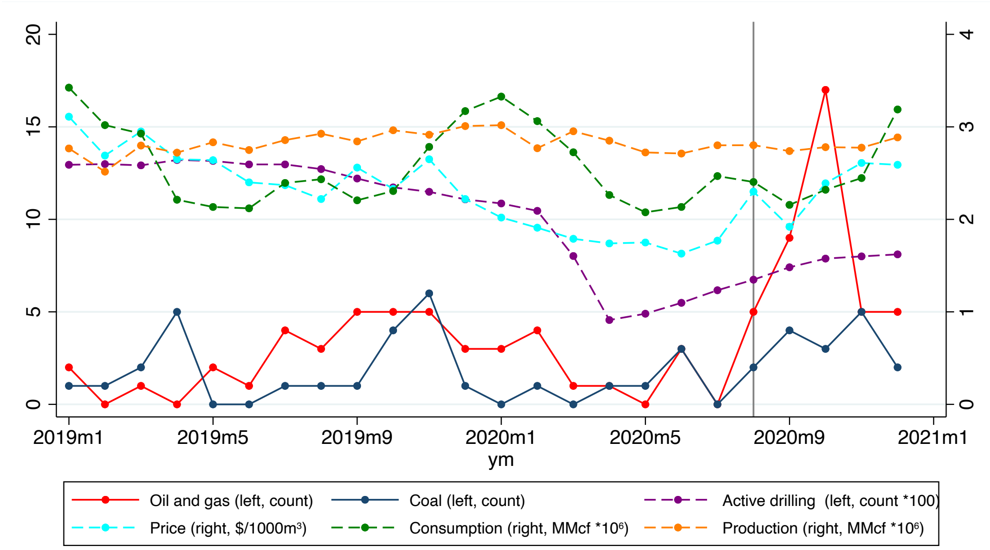
Notes: 0.1-degree sample pixels have at least one drilling well, processing plant, distribution pipeline, or compressor station inside. Methane data is aggregated to the weekly level from TROPOMI daily product Feb 8 - Dec 31 in 2019 and 2020. The upper figure plots time series of raw data. The lower figure plots residuals after controlling for year fixed effects and month fixed effects.

Figure S2: Google trends, interest in “methane” and “natural gas”



Notes: This figure shows weekly interest in google trends for word “methane” in red and “natural gas” in blue. The vertical gray line is the week of August 13, 2020.

Figure S3: Natural gas market activities



Notes: This figure shows monthly series of natural gas market activities. The first two items in the legend, i.e. oil and gas and coal, report the number of ultra-emission events at the sector-month level, same as those in Figure 3. Other four lines show the number of active drilling, natural gas price, consumption, and production, with units and y-axis specified in parentheses. The vertical gray line is August 2020.