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Natural gas flaring, respiratory health, and distributional effects ☆

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ABSTRACT

Although there is strong evidence that oil and natural gas development lead to decreases in local ambient air quality, there is less evidence of a causal link between these activities and human health. This paper explores the environmental health costs of burning natural gas by-products during crude oil extraction – flaring. We estimate the impact of flared natural gas on respiratory health by using quasi-random variation in upwind flaring generated by the interaction of wind patterns and natural gas processing capacity. Specifically, we construct a novel dataset to estimate the causal effect of increased upwind flaring on the monthly respiratory-related hospital visitation rate by using the number of upwind wells that are connected to a capacity-constrained natural gas processing facility as an instrument for monthly upwind flaring. We find that a 1% increase in the amount of flared natural gas in North Dakota would increase the respiratory-related hospital visitation rate by 0.73%. Furthermore, zip codes that were exposed to more than half of all flared natural gas extracted less than 20% of all resource wealth during the sample time period, and the zip codes exposed to a disproportionate amount of flaring tend to be economically-disadvantaged and communities of color. Our estimates indicate that the health costs constitute a material portion of the external cost of flaring, and therefore ought to be considered in global initiatives to reduce flaring.

1. Introduction

Flaring is the burning of natural gas byproducts during the crude oil extraction process. Oil producers often choose to flare the byproduct natural gas because it is not profitable to capture, transport and process. In addition to these private costs of capturing natural gas, however, there are external costs associated with the global and local air pollutants from flaring that oil producers may not consider. Driven by an impetus to reduce carbon emissions, reduce the lost value of the flared gas, and reduce nations' dependence on imported natural gas, a number of governments and intergovernmental organizations have developed programs to reduce flaring. Despite recent policy efforts, annual flaring volumes have remained high; annual global flaring in 2019 resulted in an energy equivalent greater than India's annual electricity consumption and carbon dioxide emissions comparable to those of the United Kingdom (World Bank, 2021; Energy Information Administration, 2020; Emissions Database for Global Atmospheric Research, 2019). This suggests a large potential for local health costs associated with global flaring. However, policy discussions around flaring seldom include the health cost of local air pollutants in their calculus. This lack of consideration may be due to high levels of uncertainty regarding the health damages of flaring, which depend on a swath of factors including the distribution of the populace, weather conditions and the underground composition of hydrocarbons in the region.

In this paper, we provide evidence of a causal link between natural gas flaring and human health. We take advantage of a unique dataset on well locations, flaring, weather, natural gas processing facilities, and patient-level hospital visits with the five digit zip code and health diagnostic codes for each patient in North Dakota for the years 2007–2015. The fact that flaring in North Dakota comprises about 3% of global flaring by the end of this time period makes it ideal for this study. Using an instrumental variables

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design, we estimate the impact of upwind flaring on a zip code's respiratory-related hospital visitation rate. We find that each unit of upwind flaring significantly increases the monthly respiratory-related hospital visitation rate for zip codes up to 60 miles downwind from the source. We confirm the range of this effect by finding that the positive association between flaring and satellite nitrogen dioxide readings disappears at greater distances. We further find that the damages from the flaring of natural gas are not concentrated amongst the zip codes most likely to benefit from oil and natural gas activity. Instead, the damages are more likely to be distributed across communities with little oil extraction activity, lower levels of employment, and people of color. These results suggest that during the oil boom in North Dakota, low-income communities and people of color were more likely to be exposed to the damages from flaring and other pollutants from oil extraction, while receiving fewer of the associated benefits.

We estimate that a one percent increase in upwind natural gas flaring causes a 0.73% increase in the downwind respiratory-related hospital visitation rate. This estimate indicates that if the 88% gas capture rate established by North Dakota's recent flaring policy had been in place prior to 2007, health costs from respiratory-related hospital visits in North Dakota would be reduced by $443 million USD (in 2018 dollars) over a nine year period.[1] Supplementing this figure with suggestive estimates of flaring's impact on all hospitalizations, the estimated benefits of this policy increase to $853 million USD. Although these magnitudes appear large, they are consistent with engineering estimates from the literature and are likely a lower bound since they do not incorporate the mortality or cognitive health costs from increased pollution. The rapid expansion of flaring in North Dakota, shown in Fig. 1, combined with a level of flaring that exceeded the level in all but nine countries by the end of our sample period (World Bank, 2019), suggests that our results are representative of the health damages in other areas where flaring has become a concern.

Identifying a causal relationship between the flaring of natural gas and respiratory health poses several challenges. First, there could be measurement error since exposure to flared natural gas could be endogenous to an individual's avoidance behavior (Neidell, 2009; Chay and Greenstone, 2005). Second, the oil activity that coincides with flaring also corresponds to the presence of other activities that impact local air quality, such as vehicle traffic (Fershee, 2012). Finally, increases in oil and natural gas extraction, which are associated with higher levels of flaring, may result in the migration of younger and healthier individuals for employment opportunities to the area.

Our instrumental variables approach addresses these concerns by using the capacity at nearby gas processing plants, combined with variation in wind direction, as an instrument for flaring. If a plant is near its processing capacity, then nearby wells are more likely to flare, but it should not affect other sources of pollution that impact local health. Several factors contribute to the effectiveness of our instrument. First, once a facility hits its processing capacity, the process that determines which wells are forced to flare (gathering line pressure) is quasi-random. Second, although wind directions have a seasonal pattern, there remains substantial month to month variation and variation for each month across years. This variation, for the purposes of this study, is effectively random. Third, differences in the planning and construction horizons for natural gas processing and oil drilling infrastructure makes expansions in natural gas processing capacity exogenous to contemporaneous drilling and extraction activity.

Estimates of the impact of flared natural gas on respiratory health prove robust in sign and significance across specifications and alternative identification strategies. First, we report instrumental variables (IV) estimates based on a wide variety of controls included in different combinations, across various geographic ranges, and with related outcomes. Next, to address concerns that the instrumental variables strategy itself may be generating the apparent causal effects, we report results for difference-in-differences and synthetic control based estimates of the impact of flaring on health using the timing of the North Dakota flaring policy. We find the decrease in the respiratory-related hospital visit rate for zip codes that experienced reduced flaring exposure due to the policy using this alternative empirical strategy qualitatively similar to our IV estimates. Finally, to address concerns that our instrument may correspond to changes in the composition of the downwind population and contemporaneous oil activity, we report falsification tests using appendicitis, car accidents, stroke, and trauma hospitalization rates as our outcome of interest.

Several studies provide site-specific or engineering-based results that demonstrate that flaring produces carbon monoxide, nitrogen oxides, particulate matter, and volatile organic compounds; these are all pollutants that have an unambiguously negative impact on human health (Environmental Protection Agency, 2018; Environmental Protection Agency, 1983; Sonibare and Akeredolu, 2004; Kindzierski, 1999). However, the level of these local pollutants generated by flaring depends on several factors, including underground gas composition, combustion efficiency at the flaring site, and local weather conditions (Buzcu-Guven and Harriss, 2012). In fact, a recent survey of the literature notes that "no study undertakes a systemic basin-wide inventory of flaring-based pollutants" (Agerton et al., 2020). This variability in the pollutant generating process around flaring, which is further entangled with pollutants generated from other oil extraction activities, results in high levels of uncertainty regarding the health costs of flaring. Additionally, the health costs of flaring are dependent on the population distribution in the surrounding area. For example, Russia and Nigeria are two of the world's largest producers of flared natural gas. While the plurality of flaring in Russia is in the sparsely-populated area of Khanty-Mansi in western Siberia, two million people live within four kilometers of a natural gas flare in the Niger delta (Deutsche Welle, 2008). This suggests population distribution is an important factor to consider when assessing the health damages from flaring globally.

To our knowledge, we are the first to provide quasi-experimental evidence of a causal link between flaring from oil wells and respiratory health. Currently, there is a nascent literature which finds an association between natural gas flaring volumes and health outcomes (Willis et al., 2020; Cushing et al., 2020). Of these, our work is closest to Willis et al. (2020) which finds both drilling and natural gas production are positively associated with pediatric asthmatic hospitalizations using a high-dimensional fixed effects strategy. However, they find the sign between flaring and hospitalization differs across specifications and attribute this to possible attenuation from the exclusion of flaring at nearby oil wells in their data, among other reasons. Our study moves beyond these papers in three important ways. First, our instrumental variables and difference-in-differences approaches allow us to separately identify the effect of flared natural gas from other associated oil extraction activities which may impact local health. Second, while previous studies focus on the health impacts of flaring on infants or children, we are able to examine the respiratory health response for the entire population. Third, our estimates indicate a geographic range of the health impacts from flaring up to 60 miles from the source; this is well beyond the geographic ranges considered in previous studies.

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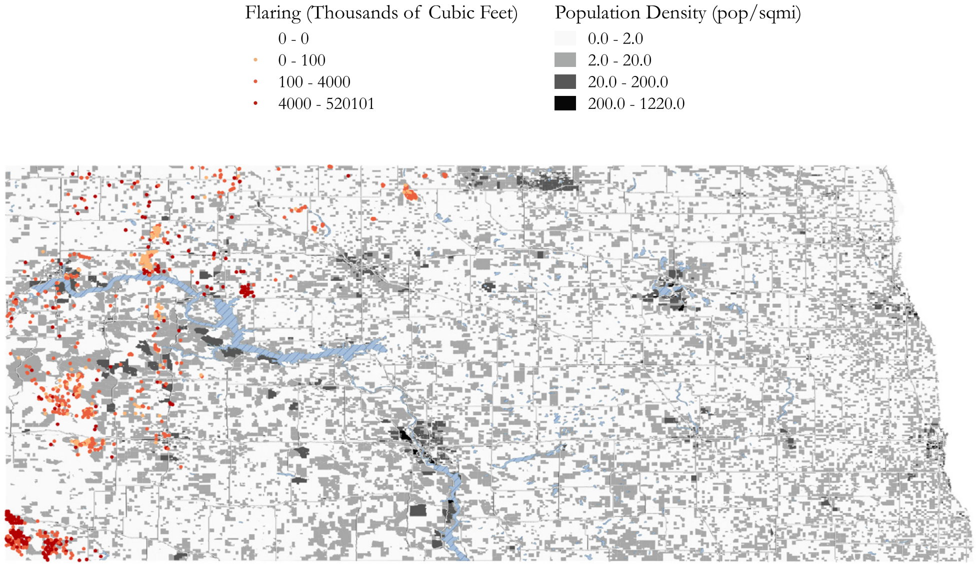
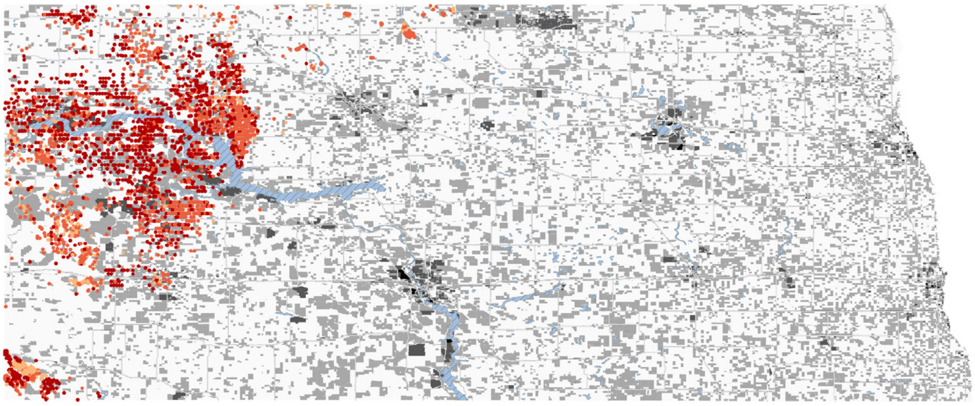
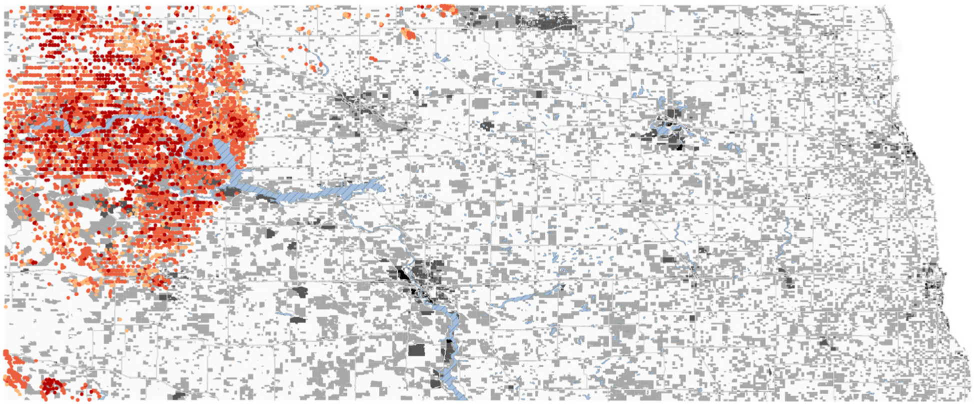
[1] The North Dakota flaring policy referred to throughout this article is the North Dakota Industrial Commission's Order 24665.



(a) 2007



(b) 2011



(c) 2015

Fig. 1. Annual Flaring in North Dakota.

In addition, our analysis on who is harmed by unconventional oil and natural gas development (UONGD) contributes to policy discussions regarding environmental justice.[2] Environmental justice concerns have shaped policy guidance issued by the Biden Administration, state climate policies, and the choice of EPA administrator (Executive Office of the President, 2021; Secretary of State of Washington, 2021; Environmental Protection Agency, 2021a). Our finding that the poor and communities of color are disproportionately exposed to flared natural gas underscores the importance of environmental justice considerations in policy discussions, in addition to building on an extensive academic literature (Banzhaf, 2011; Hsiang et al., 2019). Similarly, our finding that zip codes exposed to half of the damages from flaring extracted less than 20% of all resource wealth contributes to the literature on the distribution of the welfare impacts from shale development (Hausman and Kellogg, 2015; Black et al., 2018; Bartik et al., 2019) and highlights the import of distributional analysis in the review of policies.

Finally, our estimates contribute to a broader literature on the externalities from oil and natural gas production. This includes a growing literature that examines the general impact of air pollution from oil and natural gas development on health, but does not separately distinguish the role of flaring from other sources of air pollution in the production process (McKenzie et al., 2012; Hill, 2018; Willis et al., 2018). Outside of health impacts, effects from oil and natural gas production have been found for education, (Cascio and Narayan, 2015), public good provision (Weber, 2014), as well as air, light, noise, and water pollution (Boxall et al., 2005; Mason et al., 2015; Muehlenbachs et al., 2015; Boslett et al., 2021; Wang et al., 2014). We calculate the associated hospitalization costs of flaring to be $1.43 per mcf (thousand cubic feet) for an area with a population density of 6.2 people per square mile. This estimated health cost is comparable to both the average price of natural gas during our sample period, $5.34 per mcf, as well as the $2.19 per mcf external climate change cost from flaring noted by Agerton et al. (2020). These results indicate that global initiatives to reduce flaring, which historically focused on the climate change costs, may significantly underestimate the external cost of flaring if they do not consider the associated health damages. We believe our estimates of the health costs will better inform policymakers designing future policies to address flaring worldwide, especially in more densely populated regions where the external health costs are greater.

The remainder of the paper proceeds as follows. Section 2 describes prior research, sources of flaring, associated pollutants, and engineering-based estimates of health costs. Section 3 reports data sources, defines flaring exposure, and examines the association between satellite-observable pollutants and our measure of flaring exposure. Sections 4 and 5 presents our empirical strategy and results. Section 6 discusses the health costs from flaring and distributional implications, and Section 7 concludes.

2. Background

This section provides an overview of 1) key strands of the engineering, atmospheric science, economics, and public health literatures that motivate our study, 2) the pollutants associated with natural gas flaring and relevant prior research, 3) reasons why operators may choose to flare a valuable resource, and 4) factors that make the magnitude of the health costs from natural gas flaring uncertain.

2.1. Relevant Background Literature

Although natural gas is considered a relatively clean source of energy, relative to other fossil fuels such as coal, this is so only for processed natural gas which consists solely of methane. Unprocessed natural gas includes other hydrocarbons (natural gas liquids), as well as water vapor, carbon dioxide, hydrogen sulfide, nitrogen, oxygen, and helium (Energy Information Administration, 2006). Natural gas processing separates the various hydrocarbons (methane, ethane, propane, and butane) and removes the other contaminants. Flaring unprocessed natural gas combusts the hydrocarbons and other contaminants to produce several air pollutants. Combustion of the hydrocarbons, sulfur compounds, and nitrogen creates carbon dioxide, sulfur dioxide (SO_2), and nitrogen oxides (NO_x), respectively (Environmental Protection Agency, 2018). Furthermore, incomplete combustion of natural gas produces carbon monoxide (CO) and soot, the latter contributing to particulate matter (PM) (Environmental Protection Agency, 1983). However, as we discuss in Section 2.3, estimates on the extent of incomplete combustion and therefore the extent to which flaring generates these associated pollutants varies significantly across the literature.

There is substantial evidence within the economics and medical literatures that PM, NO_x, CO, SO_2, and volatile organic compounds (VOCs) are detrimental to human health. Moretti and Neidell (2011) find significant detrimental effects on adult respiratory health from exposure to ozone, which is mainly created from the interaction of NO_x with VOCs. Currie et al. (2009) also find pollution from CO, ozone and PM smaller than 10 μm (PM10) negatively impact infant health. Currie and Walker (2011) and Anderson (2020) link vehicle emissions, which include CO, NO_x and PM, to negative health outcomes for infants and the elderly, respectively. There is also a number of papers that find exposure to particulate matter results in increased infant mortality (Chay and Greenstone, 2003; Knittel et al., 2016).

A growing body of prior work has begun to study the impact of these associated pollutants from shale development and flaring on human health. Specific to flaring, Cushing et al. (2020) use a retrospective cohort design for the Eagle Ford in south Texas, finding that flaring activity within 5 km of maternal residence is associated with shorter gestation and reduced fetal growth. However, as discussed by Nicole (2020), this study does not separate out the impact of flaring from other environmental stressors associated with unconventional shale development. Due to these concerns, recent work by Willis et al. (2020) has taken significant care to separate out the impact of drilling, type of well, gas production, and gas flaring on individual health. In particular, their study examines pediatric hospitalizations in Texas at the zip code quarter level using models with space and time fixed effects, as well as an extensive set of covariates to account for community and zip code level shale development. They find evidence that increased zip code level drilling, well development, and gas production is associated with increased pediatric asthma hospitalizations within that zip code. However, their results regarding flaring at natural gas wells vary in sign across specifications; this is due to the exclusion of flaring from oil wells in their dataset, leading to the attenuation of flaring's estimated health impact.[3]

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[2] The Environmental Protection Agency (EPA) defines environmental justice as characterized by no group of people bearing a disproportionate share of the negative environmental consequences from industrial, governmental and commercial operations or policies (Environmental Protection Agency, 2021b).

[3] They also attribute the attenuation to potential mismeasurement of flared natural gas in the Texas Railroad Commission data noted in the literature. Recent work (Collins, 2018) indicates that mismeasurement of flaring from production data is less of a concern in North Dakota. Leyden (2019) speculates the issues with mismeasurement in Texas could be related to flared gas not being taxed. Agerton et al. (2020) note that the nature of Texas' permitting structure for flaring could also be an important factor.

This study differs from Willis et al. (2020) on a number of dimensions. Firstly, we consider the impact of flaring from both natural gas and oils wells, the latter being the source for the majority of global flaring. Additionally, we use both instrumental variables and difference-in-differences techniques to estimate the impact of flared natural gas on respiratory hospitalizations for the full population. Finally, our research design allows us to consider the health impacts of flared natural gas at significantly greater distances than those considered in previous studies.

Our decision to focus on the impact of flared natural at distances beyond the zip code or county stems from previous studies within the atmospheric sciences and economics literatures on the dispersion of – and distribution of damages from – local air pollutants. Using integrated assessment modeling, Tong et al. (2006) demonstrate that surface level emission of NO_x can change ambient air quality between 60–120 miles downwind. Mauzerall et al. (2005) demonstrate a similar phenomenon, where air monitors up to 108 miles away from the source detect changes in ambient air quality. In the economics literature, a recent paper by Holland et al. (2016), finds that 57% of damages associated with the pollution from gasoline automobiles (NO_x, CO, and CO_2) occur outside the county in which the automobile is driven. Johnsen et al. (2019) consider a geographic range of 70 miles for assessing the damages from electricity generation. In light of these studies, we consider the impact of flaring between 30 and 120 miles from the well.

More generally, our study adds to a growing set of evidence on the health impact from shale development summarized in Black et al. (2021). This includes work that examines the impact of well development on ground water quality (Muehlenbachs et al., 2015). Other studies consider the impact of air pollution from shale development on other health outcomes such asthma (Willis et al., 2018), heart attacks (Denham et al., 2021), cancer risk (McKenzie et al., 2012), infant health (Whitworth et al., 2018; Hill, 2018), and pneumonia (Peng et al., 2018). It should be noted that although many of these studies examine the impact of decreased air quality from shale development, they attribute the decrease to a variety of pollution sources throughout the production process, most prominently increased truck traffic. None of these studies consider the impact of flaring specifically.

In addition to health externalities, flaring and shale development are responsible for other local externalities. Boslett et al. (2021) note that light pollution from natural gas flaring make nighttime satellite imagery of the western plains of North Dakota comparable to the eastern seaboard. Wang et al. (2014) also find that the combustion of natural gas creates significant noise pollution distinct from other well-site activity. Outside of pollution, Cascio and Narayan (2015) find that the economic opportunities for young individuals provided by shale development lowered educational attainment. Recent work by Weber (2014) finds no evidence that shale development led to a resource curse in terms of local economic growth.

Finally, as we discuss in the following subsection, the health costs from flaring and the estimated health benefits of the North Dakota flaring policy in this paper contribute to a growing discussion on regional, national, and global flaring policies.

2.2. Natural Gas Flaring

Flaring is the practice of burning the unprocessed "wet" natural gas byproduct from oil-well production. This is typically done when the well operator is unable to transport the wet gas to a processing facility that separates the methane from other natural gas liquids. The increased profitability of unconventional oil development has resulted in substantial growth in oil production in North Dakota (Fig. 2 corresponding increase in flared natural gas (Fig. 2b). However, the practice of flaring is inefficient due to the significant value of the foregone gas, which exceeded $1 billion dollars per year in North Dakota in 2014 (Fitzgerald and Stiglbauer, 2015). As previously discussed, flaring also leads to noise, light and air pollution; the latter has the greatest impact on human health and is the focus of this study.

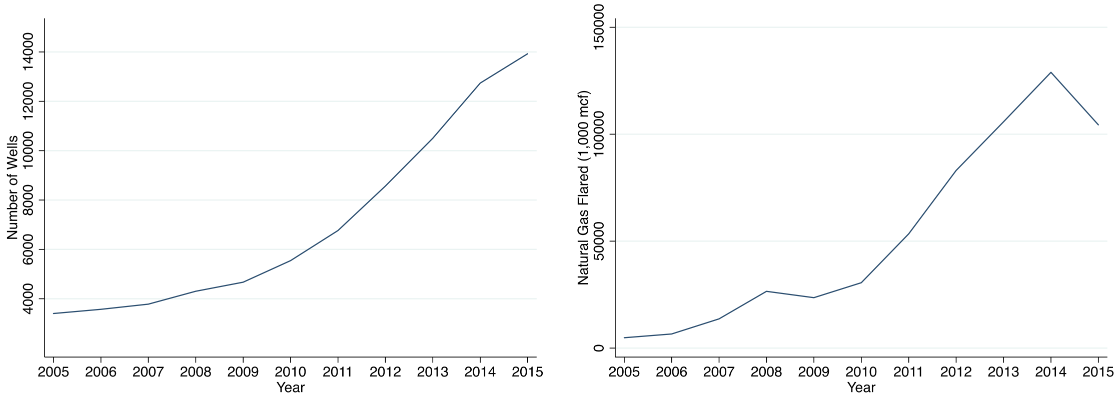
There are several institutional reasons for why well operators choose to burn, rather than sell, a valuable resource. First, oil is significantly more profitable to well operators than natural gas. The value of the oil deposits far exceeds the value of the natural gas deposits within a typical North Dakota field, therefore decisions are made with respect to oil (Kellogg, 2014). Additionally, the transportation cost for unprocessed natural gas is significantly greater than that for crude oil. While oil may be transported to a refinery via a truck or pipeline, unrefined natural gas must be transported from the well to a processing facility via gas-gathering pipelines. Second, oil wells produce more gas early in the well's life cycle when a well is less likely to be connected to a gas gathering system. Drilling generally precedes the construction of gathering infrastructure and well operators are unlikely to delay production until sufficient infrastructure is in place. Furthermore, alternatives to the use of gas gathering systems, such as re-injection or on-site electricity generation is often infeasible or cost prohibitive. Finally, a lack of capacity at nearby processing facilities may force a well that is already connected to gas gathering systems to flare regardless. It is this constrained natural gas processing capacity that provides the exogenous variation in flaring that forms the basis of our analysis in Section 4.

The third alternative to flaring or processing natural gas is to release it into the atmosphere without combustion – a process referred to as venting in the industry. However, the warming potential of methane – the main constituent of unprocessed natural gas – far exceeds that of the carbon dioxide emitted from flaring; furthermore, methane is high flammable in sufficiently high concentrations, (Ford et al., 2015). Due to these health and environmental concerns, flaring of natural gas is preferred to venting.

In an effort to reduce natural gas flaring, several states have implemented policies targeted at oil producers. The most prominent of these policies is the 2014 North Dakota flaring policy which established gas capture goals. These were initially set at 74% for October 2014 and progressively increased to 91% for 2020. Lade and Rudik (2020) find that the policy reduced flaring by 4–17% in the first year of operation. Nonetheless, oil well operators in North Dakota struggle to meet the standards set by the regulation. As of March 2019, oil producers flared about 20% of the natural gas produced in the state – considerably above the contemporaneous limit of 12% (MacPherson, 2019). Several studies consider the impact of a ban on shale development in Pennsylvania. Brown et al. (2019) estimate the potential cost of a ban using calculated local income from well royalties. Black et al. (2018) use a quasi-experimental design to examine the effect on drilling and permitting from an impact fee imposed on wells. They find that the impact fee led to "little to no declines in well permitting or drilling …in the most geologically similar subsample."

2.3. Air Pollution and Potential Health Costs from Flaring

To further motivate our primary analysis, we provide an estimate of the potential magnitude and range of the health costs from flaring in North Dakota. Estimated differences for some pollutants can vary by an entire order of magnitude across studies (Giwa et al., 2019). The heterogeneity in estimated emissions factors stems from variation in combustion efficiency, gas composition, and weather (Kleinberg, 2019). Further complicating this issue, many studies examine only a subset of the pollutants from flaring. As a recent survey of the literature notes, "no study undertakes a



(a) Total Number of Operating Wells (b) Aggregate Flaring

Fig. 2. Oil Production Activity in North Dakota 2005–2015.

systemic basin-wide inventory of flaring-based pollutants" (Agerton et al., 2020). The wide range in the potential pollutants from flaring translates to a significant range in the potential health costs from flaring and therefore the necessity of obtaining more precise estimates of these costs.

To illustrate this range, we use estimated flaring emissions factors for CO, PM, NO_x, SO_2, and VOCs from Giwa et al. (2019), Sonibare and Akeredolu (2004), and Gogolek et al. (2010). These estimates are derived from quality measures and reported flaring levels or engineering models. We combine these estimated emissions factors with county-specific flaring volumes to obtain the total increases for each pollutant. Finally, we combine these estimated pollution increases with marginal damage estimates for PM, NO_x, SO_2, and VOCs from Holland et al. (2016).[4] These pollution cost estimates are derived from various sources in the academic health literature. Column one of Table 1 provides an estimated range of total increases in the quantity of each pollutant. Column two of Table 1 provides the corresponding range of potential health costs from these pollution increases. The total estimated potential health costs from flaring range from $400 million over our sample time period ($44 million annually) to $2.190 billion ($236 million annually) in 2018 dollars.

The analysis in this subsection merely provides rough bounds for the magnitude of the health costs from the flaring of natural gas in North Dakota. Caulton et al. (2014) find that flaring efficiency at U.S. wells is significantly higher, and therefore less polluting, than in other countries. Additionally, flaring levels in the Eagle Ford in Texas are comparable to North Dakota but are closer to densely populated areas. This suggests, that our primary estimates may be a lower bound for the health costs of flaring in other regions. Nonetheless, the estimates provided by our analysis, which incorporate increased medical expenses and the associated lost wages from hospitalization, improve the understanding of health costs from flaring. Current global flaring policies, such as the World Bank's Zero Routine Flaring by 2030 initiative, strive to reduce green house gas emissions and the forgone value of flared natural gas. However, they often do not explicitly consider the health costs of flaring. Therefore this study provides germane analysis for future policymakers, and contributes to the literature measuring the externalities associated with oil and natural gas extraction.

Table 1
Range of Potential Health Costs from Flaring in North Dakota from 2007–2015.

Pollutant	Range of Amounts (Tons)	Range of Health Costs (Million $USD)
$PM_{2.5}$	[11,404–45,616]	[267–1,007]
NO_x	[19,843–74,127]	[100–374]
VOC	[25,659–94,654]	[27.9–103]
SO_2	[182–22,808]	[5–630]
CO	[89,528–553,099]	[1.36–8.42]

Notes: This tables shows engineering estimates of the amount of harmful pollutants produced by flaring (column 1) and the projected health costs of those pollutants (column 2). Ranges are due to variation in estimated emissions factors from the engineering literature. Marginal damage estimates for $PM_{2.5}$, NO_x, VOC, and SO_2 are from Holland et al. (2016). Marginal damage estimates for CO are from Litman (2015). Flaring from all wells in North Dakota between 2007 to 2015 is considered. Numbers are based on a total flared amount of 570,204,936 thousand cubic feet (mcf).

3. Data, Flaring Exposure, and Satellite Evidence

Estimating the effect of natural gas flaring on human health requires sufficient information on health outcomes and extraction activity near affected populations. For our analysis, we construct a novel dataset of extraction activity and individual health outcomes by combining a number of proprietary and publicly available datasets. We use monthly well-level production data to determine both how much wells produce and how much natural gas they flare. We combine this with information about nearby natural gas plant processing capacity to establish each well's ability to avoid flaring. We also use weather data to control for monthly trends in wind direction; this allows us to aggregate a zip code's monthly exposure to air pollution from flaring, as well as other production activities, based on the frequencies of the prevailing winds. Finally, we utilize Ozone Monitoring Instrument (OMI) satellite data from the National Aeronautics and Space Administration (NASA) to examine the relationship between our measure of exposure and measurable air quality. We now explain our use of these datasets and provide a correlation between our measure of exposure to flared natural gas and air pollution measured by the OMI.

3.1. Data

Our well-site production and gas facility processing data comes from the North Dakota Department of Mineral Resources (DMR) from the period of January 2005 to December 2015. In addition, we obtain a panel of natural gas plant processing capacity over this time period from the North Dakota Pipeline Authority. The DMR's

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[4] To obtain county-level marginal damage estimates for CO we use the scale of local damage from CO to PM found in Litman (2015).

well data contains monthly information on oil production, natural gas production and sales, flaring, and water use for 16,906 wells, giving us a total of 986,880 well-month observations. In addition, the DMR's "Gas Plant Volumes" database contains information on the level of wet natural gas received by each natural gas processing plant for each month of our sample period. Since the majority of flared natural gas comes from connected wells, a processing plant's excess processing capacity – the difference between wet natural gas received and gas processing plant's capacity – will determine the amount of flaring that occurs at any given time. Similar to Fitzgerald and Stiglbauer (2015), we assign connected wells to gas plants based on smallest great circle distance.[5] During the time period of January 2005 to December 2015, the number of active wells in North Dakota increased from roughly 4,000 to 14,000 (Fig. 2a). This increase in active wells corresponds to a 586% increase in annual processing capacity from 75,920,000 to 520,490,000 thousand cubic feet (mcf), a 668% increase in the amount of wet natural gas received by plants from 55,367,931 to 425,022,026 mcf, and a 708% increase in the amount of dry processed natural gas sold from 45,699,000 to 369,242,000 mcf.

3.1.1. Hospital Data

To measure local health outcomes we use patient-level hospital data from January 2007 to October 2015 at sixteen North Dakota hospitals from the Minnesota Hospital Association. These data include all hospital visits at these hospitals which comprises over 90% of hospital visits in North Dakota during the sample period. Each patient is assigned a unique identifier, allowing us to track repeat visits by the same patient. We also observe the five digit zip code of residence for each patient, as well as their age, sex, and time of visit. For each visit we observe the primary diagnosis code, which represents the cause of the visit. We focus on hospital visitation rates for specific respiratory diagnoses that we expect to be exacerbated by air pollution. In particular, we use the ninth revision of the International Classification of Diseases diagnostic codes (ICD-9 codes) associated with respiratory conditions due to external agents, chemicals and fumes, pneumonia and influenza, respiratory infections, bronchitis, emphysema, and other chronic obstructive pulmonary disease.[6] We also use visits for appendicitis, stroke, vehicle accidents, and other trauma as placebo tests. We aggregate these outcomes to the zip-month level for our primary analysis.

3.1.2. Weather Data

In order to calculate a measure of exposure to pollutants for an area, we use daily weather data from the North Dakota Agricultural Weather Network. These data are from 62 stations throughout North Dakota and surrounding states, shown as light blue circles in Fig. 3. We use the daily data for wind direction to calculate the percent of time the wind is blowing from each octant for each month. Next, we use ordinary kriging to interpolate the percent of time the wind is blowing from each octant for a grid spanning the entire state. We use this interpolated map to determine the percent of time the wind blows from each octant for every well and zip code centroid. We provide additional details regarding seasonal wind variation in the appendix. In the following subsection we discuss how these data are combined with our oil well data to define a zip code's exposure to flared natural gas.

3.1.3. Satellite Data

To provide a measure of air-quality in each zip code, we incorporate a satellite dataset on pollution levels from the Berkeley High Resolution Group (BEHR, (Laughner et al., 2018)). The use of satellite data allows us to circumvent the lack of ground-level air quality monitors noted in the literature (Krupnick and Echarte, 2017). The BEHR data is based on the NASA OMI satellite data and contains nitrogen dioxide (NO_2) estimates in .05x.05 degree cells (about 10 square miles) for the contiguous United States. Fig. 4 displays the fine level of detail provided by the satellite data; the small dots are the OMI grid, and the large triangles are the centroid of each zip code in North Dakota.

The atmospheric sciences literature indicates that this data is a good approximation for ground-level NO_2 (Bechle et al., 2013). We focus on NO_2 since NO_x, which include NO_2, are common byproducts of natural gas combustion when the gas is flared at less than peak efficiency (Environmental Protection Agency, 2019). The data presented significant computational challenges due to its 600 GB size; we aggregate two measures of monthly average NO_2 readings for each North Dakota zip code from the daily data, removing any observations with error codes. The main measure is the monthly average reading from the grid cell closest to a zip code's centroid. We also perform a robustness check using the monthly average of all readings across grid cells within a zip code.

One additional challenge posed by the use of this satellite data is that NO_2 measurements are presented as column densities (molecules/cm2), while ground level pollution is usually measured as parts per billion (ppb). To avoid converting the column densities to ground level units, which would require an atmospheric model and data on local topography, we follow Grainger et al. (2016) and use localized z-scores. Since we are interested in making local comparisons, observing how pollution in a given zip code compares to the surrounding region, a localized z-score provides a valid estimate of pollution for our analysis. Specifically, the z-score for zip code i in month t is defined as $z_{it} = (b_{it} - \mu_{rit})/\sigma_{rit}$, where b_{it} is the average NO_2 across zip code i in month t, μ_{rit} is the average value of b_{it} across all zip codes in the county r, and σ_{rit} is the standard deviation of the b_{it} values for the same county.

3.1.4. Supplementary Data

For our primary analysis, we leverage data from the American Community Survey (ACS) and the U.S. Energy Information Administration (EIA). We obtain zip code level population, housing and income data for 2007, 2010, and 2011–2015 from the ACS; we interpolate survey data between 2007 and 2010 to obtain data for 2008 and 2009, because ACS datasets for these years are not available. Additionally, we collect monthly average oil prices for North Dakota from the EIA's First Purchase Price by Area dataset.

To conduct our mortality analysis, we consider the mortality rate per 100,000 for those over 65. The mortality data come from the Center for Disease Control and Prevention's Underlying Cause of Death database. The data provide information on the number of deaths for residents over 65 at the county year month level, and is bottom coded such that months with less than 10 deaths are omitted. This top coding results in 334 uncensored observations for nine counties within geographic range of an active well during our sample time period. We obtain the total population of individuals over 65 at the county level from the National Bureau of Economic Research's U.S. Intercensal County Population Data for 1969–2018.

For our distributional analysis, we calculate the average of 2011–2015 ACS zip code level data to construct the demographic

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[5] We examine the validity of this assumption using an archived dataset of gas gathering infrastructure from MapSearch for the time period of late 2010. We find that for wells which sold natural gas during this time period and successfully matched to this infrastructure data, smallest great circle distance corresponds with the closest natural gas processing plant via natural gas pipelines 88% of the time. This reinforces our belief that the closest natural gas processing facility via smallest great circle distance likely predicts the nearest processing plant via gas gathering lines.

[6] Specifically we classify visits with primary or additional diagnostic codes of 460–466, 480–488, 490–494, 496, 503, 504, and 506 as respiratory-related visits.

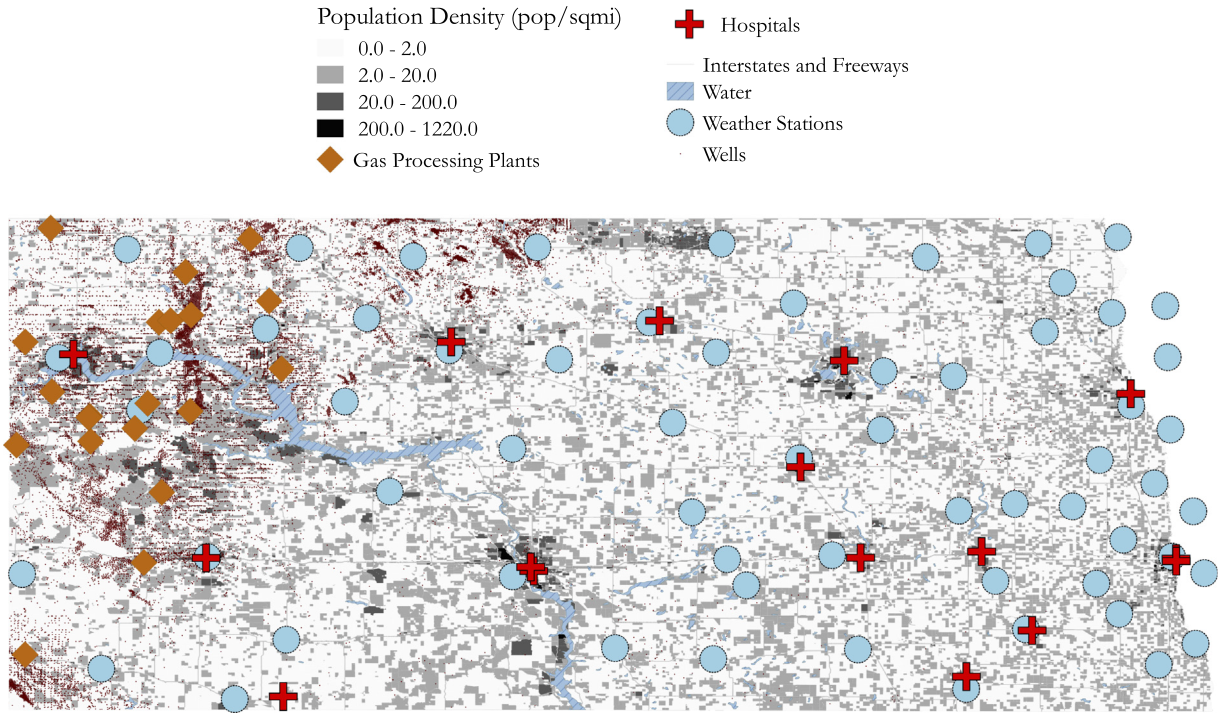

Fig. 3. Location of gas processing plants, weather stations, hospitals and oil wells in North Dakota.

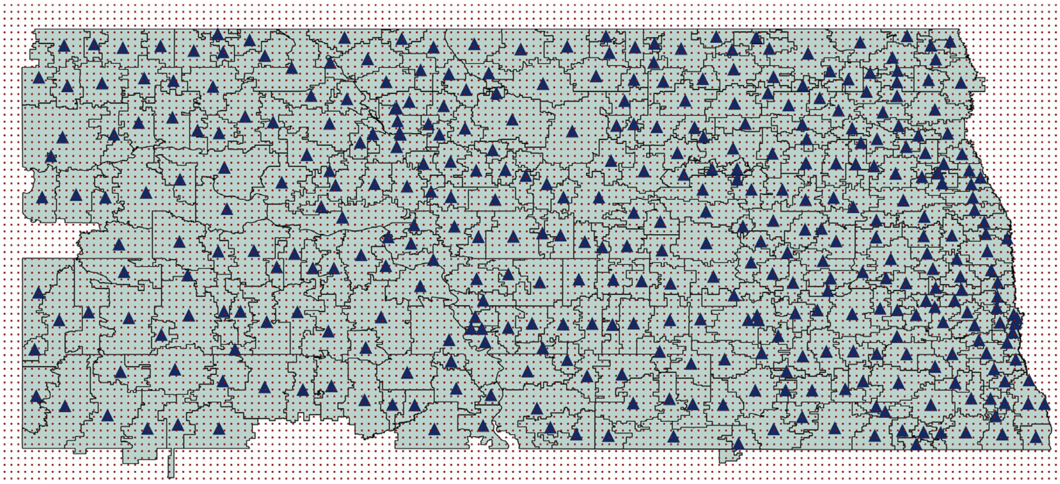

Fig. 4. OMI Grid and Zip Code Centroids in North Dakota.

and employment information. Finally, we obtained daily ground level NO_2 readings and location data for eight monitors in North Dakota from the EPA. We average the daily one hour samples to the monthly level for a supplementary analysis.

3.2. Measuring Exposure

We combined kriged weather data together with well data to calculate a measure of exposure to flaring and air pollution from other well activities at the zip code level. For each zip code centroid, we calculate a weighted average of the monthly upwind flaring at wells within 30, 60, 90 and 120 miles, weighted by the percent of time the wind is blowing from each octant. Fig. 5 shows a simple example where the dashed lines show the eight octants within a circle of a given radius, e.g. 30 miles. Each point represents

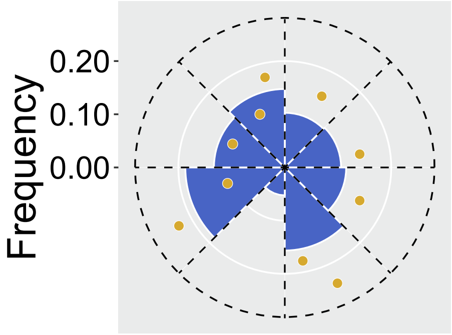

Fig. 5. Measuring Exposure to Pollution Sources.

a well within the specified distance from the zip code centroid; for our measure of exposure, we consider the flaring from all wells contained in the circle. The blue shaded area represents the proportion of time (frequency) that the wind blew from each octant to the zip code centroid. The farther from the centroid that this area extends, the more often the wind was blowing from that direction in that month.

We use the frequency as weights, $Wind_{iqt}$, to compute a weighted average of the zip code's total exposure to upwind flaring in month t as follows:

$$Up\ wind\ Flaring_{it} = \sum_{q=1}^{8} Wind_{iqt} Flaring_{iqt}.$$

$Flaring_{iqt}$, is the total amount of natural gas flared from all wells in octant q within a radius of 30, 60, 90, or 120 miles from zip code i's centroid in month t. We create similar measures, $UpwindOil_{it}$, $UpwindDrilling_{it}$ and $UpwindWells_{it}$ to control for upwind oil production, wells that are being drilled, and operating wells, respectively. These variables are meant to control for the health effects of air pollution from the oil production process, the drilling of new wells and other well operations, respectively, separate from the healths effects of pollution from natural gas flaring. We also compute the total oil production, total number of wells and the total number of new wells drilled within the same radius, without weighting by the frequencies, $Wind_{iqt}$.

3.3. Estimation Data

Table 2 presents a summary of the combined zip-month level data by exposure distance. Columns 1 and 2 present the mean and sample standard error for zip codes with at least one flaring well within 30 miles of the zip code centroid. Columns 3 and 4 correspond to zip codes with a well within 60 miles, columns 5 and 6 extend this range to 90 miles, and columns 7 and 8 extend it to 120 miles. There are 11,550 zip-month observations within 30 miles of an active well, 15,225 observations within 60 miles, 19,845 observations within 90 miles, and 23,835 observations within 120 miles. The average zip code is downwind from about 42,280 mcf of monthly flared natural gas at a range of 30 miles and 300,572 mcf when the range is extended to 120 miles. The average zip code is within range of 596 to 3,408 active wells. Each zip code has an average population between 1,459 residents and 1,816 residents depending on the distance to an active well considered. Across all geographic ranges, the average zip code's hospital visitation rate is between 0.785 and 0.828 with roughly a fifth of those visits classified as respiratory-related.[7] Overall, it is clear that we have a significant population size and number of respiratory cases with a total population of 180,000 and more than 32,000 total respiratory-related hospital visits for the 30 mile range alone. With the larger geographic ranges encompassing both a larger sample population and total respiratory visits.

To show a suggestive relationship between upwind flaring and respiratory illness, Fig. 6 plots the zip code monthly average flaring exposure and respiratory-related hospitalization rate across years. There is an evident upward movement between these two series. However, this relationship is only suggestive given the evidence of possible confounding variables presented in panels B and C of Table 2.

Panels B and C of Table 2 break up the observations based on whether the zip-month observation has a monthly level of flaring exposure that is in the top or bottom quartile of the distribution. The zip codes in the top quartile of exposure have slightly higher levels of atmospheric NO_2 than observations in the bottom quartile, consistent with increased pollution from flared natural gas. Focusing on observations within a range of 60 miles, individuals from zip codes in the top quartile of exposure were younger and more likely to be male than individuals from areas in bottom quartile of exposure. These demographic differences likely explain why high exposure zip-month observations exhibit a lower rate of respiratory-related hospital visits. We do not expect areas with higher levels of exposure to have a higher mean rate of respiratory-related hospital visits if those high exposure areas have younger and healthier patients. Additionally, Figs. 7a and b provide evidence of demographic change over time in North Dakota: as oil well and flaring activity increased, the average age decreased and the ratio of males increased in the population of interest.

In the following section, we present our instrumental variables strategy which addresses the apparent endogeneity between the level of flaring exposure and local demographics, as well as other potential confounders that vary over time. In the following subsection, we further examine the relationship between flaring exposure and satellite NO_2 readings.

3.4. Association Between Flaring and Pollution

We begin by documenting a positive correlation between monthly upwind flaring and satellite NO_2 readings, which is consistent with the atmospheric sciences and engineering literature that nitrogen oxides are a common pollutant from natural gas flaring. The use of satellite data allows us to circumvent the sparsity of ground-level air quality monitors noted in the literature (Krupnick and Echarte, 2017). However, we also provide estimates using observations from the six to eight ground level NO_2 monitors within range of an active well. These regressions suggest a link between the flaring of natural gas and the spread of pollutants harmful to human health.

For the analysis based on satellite readings, we analyze two measures of a zip code's monthly NO_2 as the outcome of interest. The first monthly measure of NO_2 from satellite readings is the local z-score z_{it}; this measure mitigates concerns regarding mismatch between atmospheric column density and ground level NO_2 readings by focusing on within-county variation in NO_2. This normalized measure of pollution allows us to measure the impact of flaring exposure even if satellite NO_2 readings have a significant geographic correlation. If one zip code has a higher level of flaring exposure compared to its neighbors, then it will also have a higher z-score relative to them. The second measure is a monthly average of NO_2 readings for the grid cell closest to the zip code centroid. Thus, here we use only the monthly readings for the grid point (dot) closest to each zip code's centroid (triangle) in Fig. 4. Grainger et al. (2016) find that atmospheric NO_2 readings explain a significant portion of the variation in ground level NO_2 estimates, particularly in small areas such as zip codes.

In both cases, we estimate the following specification:

$$z_{it} = \beta_0 + \beta_1 \cdot log(UpwindFlaring_{it}) + \gamma_i + \delta_t + \varepsilon_{it}, \tag{1}$$

where z_{it} is the measure of NO_2 pollution for zip code i in month t. $UpwindFlaring_{it}$ is the monthly flaring exposure, γ_i is the zip code fixed effect and δ_t is the month of sample fixed effect. Standard errors are clustered at the zip code level to account for zip code specific shocks.

The results are shown in Table 3. Each column corresponds to a different range, starting with zip codes within 30 miles of an active well, and extending to zip codes within 120 miles of an active well. Panel A of Table 3 presents results from regressions using the local z-score z_{it} as the outcome. Panel B shows results for the regressions

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[7] The visitation rate is one hundred times the number of hospital visits divided by the zip code's population. Thus a value of one corresponds to one percent of a zip code's population visiting a hospital every month.

Table 2
Summary Statistics.

	30 Miles		60 Miles		90 Miles		120 Miles	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Panel A: Whole Sample								
NO_2[†]	34.76	0.0046	34.79	0.0040	34.79	0.0034	34.78	0.0031
Respiratory Visit Rate*	0.166	0.0025	0.164	0.0022	0.168	0.0021	0.173	0.0020
Hospital Visit Rate*	0.788	0.0060	0.785	0.0056	0.808	0.0054	0.828	0.0051
Upwind Flaring (mcf)	42,280	917	132,332	1,956	225,115	2,609	300,572	2,984
Upwind Constrained Wells	41.05	0.55	114.1	1.17	188.3	1.60	260.5	1.92
Upwind Wells	76.53	0.83	221.8	1.96	361.3	2.77	487.2	3.29
Upwind Oil (bbls)	149,606	2,794	48,1221	6,245	797,253	8,340	1,045,418	9,464
Upwind Drilled Wells	4.711	0.091	14.73	0.20	24.57	0.27	32.91	0.31
Wells in Range	596.5	6.47	1,667.0	14.8	2,609.2	19.4	3,408.5	21.6
Oil in Range (bbls)	1,157,370	21,658	3,588,319	45,158	5,752,105	55,676	7,295,336	59,415
Drilled Wells in Range	37.10	0.71	110.4	1.46	176.3	1.75	226.5	1.86
Population	1,711.3	41.3	1.459.4	31.7	1,816.8	35.6	1,613.5	29.8
Observations	11,550		15,225		19,845		23,835	
Panel B: Bottom Quartile of Exposure								
Upwind Flaring (mcf)	71.38	1.73	320.8	6.27	296.3	5.48	563.8	7.82
NO_2	34.83	0.0087	34.81	0.0086	34.77	0.0067	34.71	0.0064
Respiratory Visit Rate*	0.188	0.0045	0.156	0.0051	0.174	0.0051	0.190	0.0048
Hospital Visit Rate*	0.810	0.0100	0.774	0.013	0.848	0.014	0.898	0.013
Avg. Zip Age[‡]	42.28	0.16	48.66	0.12	44.38	0.15	47.84	0.12
Zip Sex Ratio (M/F)[‡]	127.4	4.87	111.1	0.43	113.0	0.51	110.8	0.43
Observations	2,888		3,807		4,962		5,959	
Panel C: Top Quartile of Exposure								
Upwind Flaring (mcf)	154,905	2,747	444,982	5,100	740,761	5,888	961,044	6,291
NO_2	34.80	0.0082	34.85	0.0070	34.89	0.0059	34.89	0.0053
Respiratory Visit Rate*	0.154	0.0044	0.154	0.0037	0.160	0.0034	0.170	0.0034
Hospital Visit Rate*	0.754	0.011	0.775	0.0097	0.782	0.0084	0.802	0.0078
Avg. Zip Age[‡]	40.78	0.15	41.64	0.13	41.91	0.12	43.14	0.11
Zip Sex Ratio (M/F)[‡]	113.4	0.45	118.8	2.36	149.3	5.49	144.9	4.62
Observations	2,887		3,806		4,961		5,958	

Notes: This tables shows the summary statistics of the zip code month observations of our analysis. Columns (1) - (2) present the sample mean and standard error for zip codes that are within 30 miles of an active well at least once during the sample period. Columns (3) - (4) expand this range to 60 miles. Columns (5) - (6) expand this range to 90 miles. Columns (7) - (8) expand this range to 120 miles. *Hospital visitation rates are per capita, where a value of 1.0 corresponds to 1% of the zip code's population visiting the hospital. [†]Due to gaps in satellite coverage in NO_2 readings, we only observe 8,554, 11,345, 14,896, and 18,196 observations for each of the four geographic ranges. [‡]Due to a lack of annual ACS data for these characteristics prior to 2010, numbers correspond to post 2009 observations only.

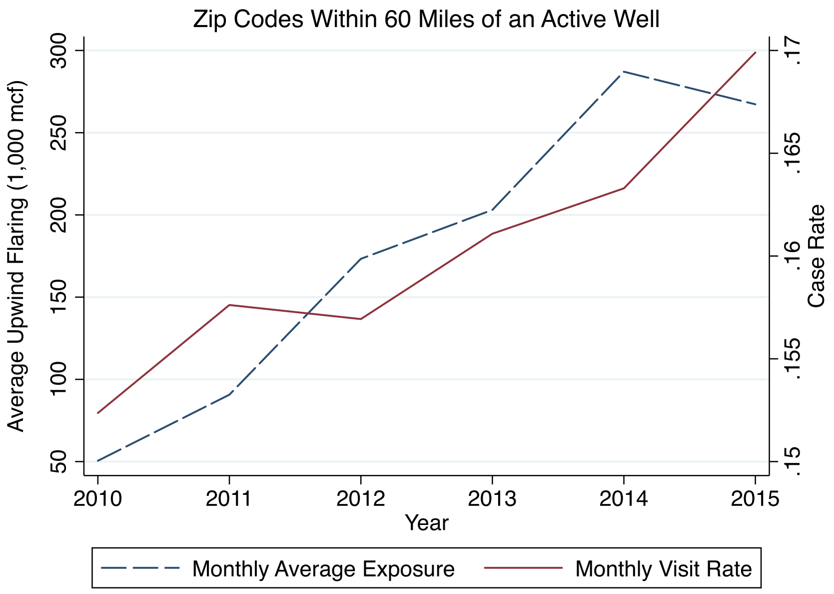

Fig. 6. Flaring Exposure Levels and Respiratory Hospitalization Rates.

using the average monthly NO_2 reading for the grid cell closest to each zip code's centroid as the outcome. In both cases, there is a positive and statistically significant correlation between flaring 30 to 60 miles upwind and atmospheric NO_2 readings. Panel B results in columns 3 and 4 for zip codes within 90–120 miles of an active well indicate a smaller, but still positive, correlation between flaring and atmospheric NO_2 that is only statistically significant at the 10% level. Overall, there is a strong positive correlation between atmospheric NO_2 and our measure of a zip code's exposure to upwind flaring from wells within 30 to 60 miles. Furthermore, the positive correlation diminishes at greater distances, consistent with findings in the atmospheric sciences literature.

(a) Average Zip Code Gender Ratio (b) Average Zip Code Age

Fig. 7. Changing Demographics in the Bakken.

Table 3
Ordinary Least Squares Estimates of Flaring and NO_2 Readings.

	(1)	(2)	(3)	(4)
	30 Miles	60 Miles	90 Miles	120 Miles
	b/se	b/se	b/se	b/se
Panel A: Z-Score NO_2 Reading				
Log(UpwindFlaring)	0.025***	0.017**	0.003	0.002
	(0.007)	(0.008)	(0.010)	(0.009)
Dep. var. mean	−0.042	−0.005	0.006	−0.014
N	9,498	12,528	16,344	19,911
R^2	0.003	0.001	0.000	0.000
Panel B: Log Average Center Zip Code NO_2 Reading				
Log(UpwindFlaring)	0.023***	0.021***	0.009*	0.008*
	(0.003)	(0.004)	(0.005)	(0.004)
Dep. var. mean	34.76	34.79	34.79	34.78
N	8,554	11,345	14,896	18,196
R^2	0.382	0.382	0.370	0.378
Panel C: Average Air Monitor NO_2 Reading				
Log(UpwindFlaring)	0.107*	−0.020	0.017	−0.018
	(0.060)	(0.061)	(0.138)	(0.133)
Dep. var. mean	4.961	5.057	6.234	6.234
N	528	636	744	744
R^2	0.626	0.603	0.766	0.766
	15–30 Miles	30–60 Miles	60–90 Miles	90–120 Miles
Panel D: Donut Specification Z-Score NO_2 Reading				
Log(UpwindFlaring)	0.021**	0.002	−0.010	0.001
	(0.008)	(0.009)	(0.011)	(0.012)
Dep. var. mean	−0.042	−0.005	0.006	−0.014
N	9,498	12,528	16,344	19,911
R^2	0.003	0.002	0.001	0.000
Panel E: Donut Specification Log Average Center Zip Code NO_2 Reading				
Log(UpwindFlaring)	0.017***	0.009**	−0.003	0.004
	(0.003)	(0.004)	(0.004)	(0.004)
Dep. var. mean	34.76	34.79	34.79	34.78
N	8,554	11,345	14,896	18,196
R^2	0.382	0.384	0.373	0.378
Panel F: Donut Specification Average Air Monitor NO_2 Reading				
Log(UpwindFlaring)	0.135*	0.112*	−0.003	−0.048
	(0.072)	(0.062)	(0.148)	(0.172)
Dep. var. mean	4.961	5.057	6.234	6.234
N	528	636	744	744
R^2	0.630	0.632	0.769	0.768
Zip Code Fixed Effects	Y	Y	Y	Y
Month Fixed Effects	Y	Y	Y	Y

Notes: This table reports ordinary least squares (OLS) regressions of zip code NO_2 z-score, average monthly atmospheric column density NO_2 readings (molecules/cm2) for the grid point closest to the zip code centroid, and local NO_2 air monitor readings on upwind natural gas flaring for zip codes in North Dakota from 2007–2015. Z-scores in panels A and D are derived from the average of satellite grid cells within the zip code. For panels A, B, D, and E standard errors are clustered at the zip code level. For panels C and F standard errors are Huber–White robust standard errors. The panel is not balanced due to gaps in satellite coverage during the sample period. Panels C and D include the log of the total upwind natural gas flared from wells within the inner portion of the donut as an additional control. *** indicates significance at the 1% level, ** at the 5% level, * at the 10% level. **Sample:** Column (1) considers monthly observations from 110 zip codes that were within 30 miles of at least one active well during the sample period. Column (2) considers monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period. Column (3) considers monthly observations from 189 zip codes that were within 90 miles of at least one active well during the sample period. Column (4) considers monthly observations from 227 zip codes that were within 120 miles of at least one active well during the sample period.

Next, Panels D and E present donut specifications that consider exposure from flared natural gas from the last 15 to 30 miles of the geographic range. The natural gas flared in the inner portion of the donut is included as an additional control; this allows us to confirm that our measure of exposure captures flaring from the outer portion of the donut, and is not driven solely by flaring near the zip code centroid. Results from column 1 indicate that the correlation between NO_2 and natural gas flared 15 to 30 miles from the zip code centroid is both statistically significant and of similar magnitude to the results in Panels A and B. Column 2 demonstrates a similar result, with the estimated correlation between atmospheric NO_2 and natural gas flared from wells 30 to 60 miles upwind from a zip code being positive and statistically significant for the zip code centroid NO_2 readings in Panel E. In columns 3 and 4, there is no evidence of a statistically significant relationship between average zip code NO_2 readings and flared natural gas from wells 60 to 90 and 90 to 120 miles from the zip code centroid.

As a final robustness check, we estimate Eq. (1) using the average monthly NO_2 air quality index value for pollution monitors in a zip code.[8] The number of these observations is limited to readings from the six to eight NO_2 air quality monitors within the specified geographic ranges. However, results using this data in Panels C and F are qualitatively similar to those obtained using satellite data. For the donut specifications in Panel F, flaring is positively correlated with the log of ground level NO_2 readings up to a geographic range of 60 miles. With the positive correlation losing statistical significance and changing sign at greater distances. In the appendix, we provide the same analysis using an alternative measure of z-scores, the average satellite NO_2 for all cells in a zip code, and the log of the air quality index value. Results from these alternative specifications are qualitatively similar.

4. Methodological Challenges and our Empirical Approach

The goal of this study is to determine the impact of natural gas flaring on individuals' health. However, there are a number of challenges associated with estimating the causal impact of flaring on human health.

First, there is the issue of omitted variable bias because many other activities associated with natural gas flaring can negatively impact ambient air quality. For instance, unconventional oil and natural gas development (UONGD) can lead to an increase in vehicle traffic (Graham et al., 2015) and its corresponding pollutants. In addition, activities such as drilling or accidents such as methane leaks could also worsen air quality (Hausman and Muehlenbachs, 2019).

Second, there may be omitted variable bias related to changes in the population that coincide with natural gas flaring. Job opportunities from UONGD could incentivize younger, healthier people to migrate to areas with increased natural gas flaring (Cascio and Narayan, 2015). In addition, royalty payments or increased incomes from UONGD could also induce people to spend more on their health.

A third concern arises about the potential endogeneity in individuals' exposure to the pollution from flared natural gas. People who are the most susceptible to the pollution may engage in avoidance behavior to mitigate their level of exposure (Neidell, 2009). This may include staying indoors or even migrating away from areas with high levels of pollution (Banzhaf and Walsh, 2008).

The following sections elaborate on how our main specification deals with these challenges in two ways: (i) the use of wind variation interacted with natural gas processing capacity as an instrument for flaring, and (ii) the use of extensive controls for UONGD and demographics. In addition, we provide specific examples of potential violations of the exclusion restriction and explain how they are not a concern in our setting.

4.1. Empirical Approach

To address the challenges in the previous section, we use two-stage least squares (2SLS) and estimate the following:

$$\begin{aligned} log(UpwindFlaring_{it}) = \alpha_0 + \alpha_1 \cdot log(ConstrainedWells_{it}) \\ + X\prime_{it}\psi + W\prime_{it}\zeta + \lambda_i + \kappa_t + \eta_{it}, \end{aligned} \tag{2}$$

$$\begin{aligned} Health_{it} = \beta_0 + \beta_1 \cdot log(\widehat{UpwindFlaring}_{it}) + X\prime_{it}\theta + W\prime_{it}\delta + \gamma_i \\ + \phi_t + \varepsilon_{it}. \end{aligned} \tag{3}$$

Eq. 3 is the second-stage and Eq. 2 is the first-stage regression. The dependent variable, $Health_{it}$, is the rate of hospital visits in zip code i in month t for a given condition, e.g. respiratory-related visits. Focusing on the rate of respiratory-related hospital visits has several advantages. By using the per capita rate we do not have to make any assumptions about zero valued observations. In addition, by focusing on a broad range of respiratory-related ICD-9 codes, the data provide sufficient variation for identification.

As we discussed in Section 3.4, our main independent variable of interest is a zip code's exposure to upwind flared natural gas. However, there are a number of other pollution generating activities that are associated with higher levels of flaring, such as well drilling and vehicle traffic. Regarding these confounding sources of pollution, the vector $X\prime_{it}$ includes a set of controls related to oil production and drilling to capture trends in shale development and the resulting co-pollutants over time. In particular, we include both the number of wells being drilled upwind, the total amount of oil produced upwind, and the number of upwind wells within the specified geographic range. We also include the total number of wells being drilled, oil produced, and active wells within range of a zip code.

With respect to increased incomes from UONGD, it is possible that individuals may utilize more health care after their incomes increase either from royalties or improved employment opportunities. Ignoring this effect could lead us to under-estimate the impact of natural gas flaring on health. The vector $W\prime_{it}$ includes controls for average income in the zip code as well as housing values, which serve as a proxy for royalties (Muehlenbachs et al., 2015).

We also include zip code and month fixed effects: λ_i and γ_i, and κ_t and ϕ_t. The zip code fixed effects control for time invariant characteristics within a zip code and the month fixed effects capture seasonal trends that affect health and upwind flaring. Finally, ε_{it} and η_{it} are the error terms that include all of the other health and upwind flaring shocks in zip code i, month t that we have not controlled for.

In addition to our primary analysis with the respiratory-related visitation rate outcome variable, in the appendix we outline and estimate a conditional Poisson regression model using the count of respiratory-related hospital visits from a zip code as the dependent variable. Specifically, we adopt the control-function approach outlined in Lin and Wooldridge (2019); we account for the endogeneity of exposure to flared natural gas by including the residual from the estimation of Eq. 2 into a second stage conditional Poisson model. In the appendix, we discuss concerns with this alternative approach, namely coefficient interpretability, and goodness of fit.[9]

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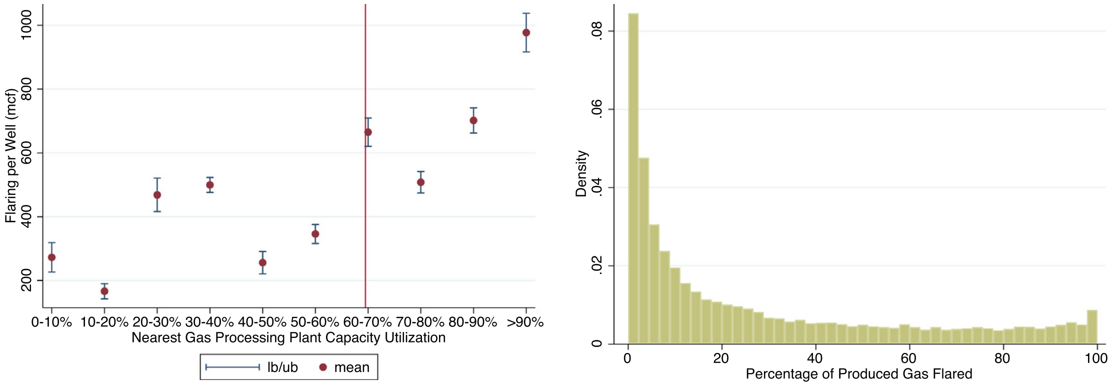
[8] We use Huber–White robust standard errors for this specification due to the limited number of zip codes.

[9] Schlenker and Walker (2015) use the same control-function approach in estimating the count of hospital visits from a zip code as an alternative to a visit rate outcome. They also note similar difficulties with interpretation of the impact of pollution exposure, their primary independent variable.



(a) Average Flaring and Nearby Processing Capacity (b) Distribution of Flaring Across Constrained Wells

Fig. 8. Natural Gas Processing Capacity Over Time.

However, results are qualitatively similar to our primary analysis with the hospital visit rate outcome, $Health_{it}$ below.

4.2. First Stage Specification: Constrained Wells Upwind as an Instrument

Our coefficient of interest is β_1, the coefficient on our measure of a zip code's exposure to upwind natural gas flaring. As previously discussed, there are a number of challenges in using observational data to estimate a causal relationship between flaring and human health. Our ideal experiment would randomly assign different levels of flaring to different areas in order to be able to separate the effect of flaring from other aspects of oil production. Of course this is not feasible, so we use an instrumental variables approach.

To instrument for $log(UpwindFlaring_{it})$ in Eq. 2, we use a weighted sum of the number of wells whose nearest gas processing plant is near its processing capacity:

$$Log(ConstrainedWells_{it}) = Log\left(\sum_{q=1}^{8} ConstrainedWells_{iqt} \cdot Wind_{iqt}\right). \tag{4}$$

$ConstrainedWells_{iqt}$ is the number of wells in octant q within the radius of zip code i's centroid in month t whose nearest gas processing plant is above 60% of its processing capacity.[10] $Wind_{iqt}$ is the percent of time in month t that the wind in zip code i's centroid is blowing from octant q, as was shown in Fig. 5.

The choice of a 60% capacity utilization threshold at the month level for defining a plant as constrained, and therefore more likely to flare, is motivated by the influence of natural gas processing capacity on flaring. According to Dave (2009), "Even after the oil and gas well has been connected to a gas-gathering pipeline and processing facility, there are still times when the well may flare intermittently, this is generally due to excess line pressures" from a lack of processing capacity at the facility to which the well is connected. This is supported by Fig. 8a which shows a dramatic increase in the average level of flaring for wells connected to a processing plant that exceeds this 60% monthly threshold. Wells connected to a plant below the monthly threshold flare 418 (mcf) on average, compared to 720 (mcf) for wells connected to a plant above the threshold. The finding that wells flare at all levels of capacity utilization is a consequence of the monthly nature of the data: given the significant daily variation in gas production (Vaughn et al., 2018), there could be a number of days within the month where production exceeds capacity, even if the average utilized capacity over the entire month is low.

There are a number of characteristics that make the number of upwind wells connected to a constrained natural gas processing plant, conditional on the level of upwind oil production activity $X\prime_{it}$, well-suited for our analysis. This is due to the number of upwind constrained wells being both exogenous to changes in other factors that determine respiratory health downwind and predictive of the level of flaring exposure.

First, we argue that for a given constrained processing plant, the determination of which wells are forced to flare is quasi-random. The line pressure that forces a well to flare is determined by a combination of whether there are pooled natural gas liquids in the line near the well, when the well operator last cleared the line, and the productivity or pressure from other wells connected to the constrained processing facility. The quasi-randomness of this process is demonstrated in the data. Fig. 8b plots the distribution of the percentage of gas produced from a well that is flared, conditional on being connected to a constrained plant. Across wells connected to a constrained plant, the majority flare more than 15% of the gas produced, and of those, the percentage flared is evenly distributed, with a small spike at 100%. Given this relatively flat distribution, it is unlikely that there are systemic differences in the underlying characteristics of the wells forced to flare by being connected to a constrained plant, which would violate our exclusion restriction.

Second, there is significant variation in the maximum capacity of natural gas processing facilities over time. Fig. 9 demonstrates how increases (decreases) in natural gas processing capacity lead to decreases (increases) in the proportion of active wells defined as constrained (i.e. connected to a constrained processing facility). Furthermore, conditional on the total number of active wells, a change in the number of constrained wells corresponds to a change in the aggregate level of flared natural gas. Consistent with the fact that during our sample period, the majority of flared natural gas came from wells connected to processing infrastructure.

Third, our instrument for flaring exposure is a function of the number of these wells connected to a constrained plant that are *upwind* from a zip code. North Dakota is subject to significant seasonal variation in wind direction; the wind blows predominantly from the west to north and from the south during summer (Enz, 2003). Any such seasonality in weather patterns is of course captured by our month fixed effects, making the identifying variation in our instrument the variation in wind direction within a month interacted with the expansions in processing capacity. Fig. 10 demonstrates that there is substantial variation in wind direction within a month across years. Although it is difficult to disentangle the importance of abnormal wind patterns versus expansions in

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[10] As an alternative specification in the appendix, we raise the threshold to whether the gas processing plant is above 70% of its processing capacity.

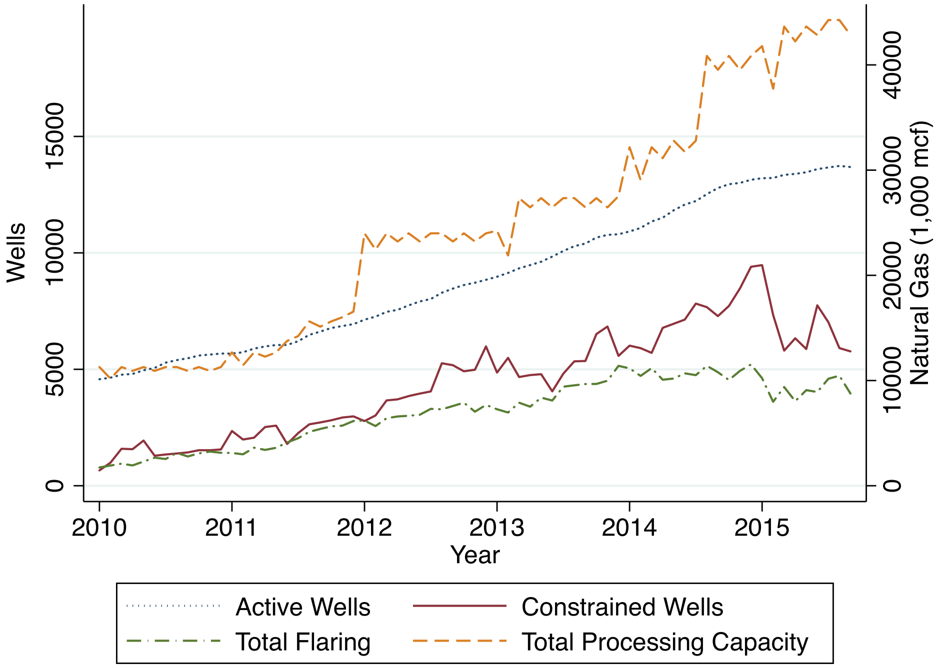

Fig. 9. North Dakota Natural Gas Flaring and Processing Capacity.

processing capacity in the determination of the total number of constrained wells upwind from a zip code, we attempt to quantify the importance of these two sources of variation in the appendix. We find that abnormal wind patterns explain 4.5% and total processing capacity explains 12.2% of the variation in the number of constrained wells upwind from a zip code. Furthermore, conditional on the full set of controls including month and zip code fixed effects, a one standard deviation increase in processing capacity corresponds with a 35.14% decrease in the number of constrained wells upwind. Where as, a one standard deviation increase in the number of constrained wells attributable to abnormal wind patterns, corresponds with a 21.2% increase in the overall number of constrained wells upwind from a zip code for the month. These results indicate that for our setting, within month variation in wind direction and changes in processing capacity both play significant roles in the determination of the number of constrained wells upwind from a zip code.

The validity of our instrument requires that, after controlling for UONGD activities and demographics, the only link between the number of constrained upwind wells and a zip code's respiratory health is via flared natural gas. Violations of the exclusion restriction would occur if the number of upwind constrained wells were a proxy for other sources of air pollution caused by UONGD related activities or corresponded with changes in downwind demographic characteristics. One example would be if more wells were drilled due to the expansion of processing capacity, bringing additional workers and sources of pollution to the region. However, this potential violation is unlikely; drilling decisions are made with respect to oil because "producers see the associated gas as a less valuable byproduct of crude oil production, which can be sacrificed" (Ehrman, 2014). Fig. 9 provides additional support for this assertion: following expansions in processing capacity, the upward trend in the number of active wells remains constant; we do not observe sudden increases in the number of active wells before or after the expansions.

Other potential violations of the exclusion restriction would occur if increased upwind processing capacity corresponded with changes in the operation of wells or the behavior of individuals downwind. For instance, if wells became more productive or if individual incomes rose dramatically following the processing capacity increase, and these changes are not captured by our controls, then our instrumental variables estimates would be biased. Given our rich set of controls for upwind production, total production in the zip code's geographic region, drilling, average annual income for the zip code, and other zip code characteristics, it is difficult to think of any additional link to either co-pollutants from oil production activities or changes in zip code demographic characteristics. Therefore, we consider monthly variation in the number of upwind wells connected to a constrained natural gas processing facility as plausibly exogenous to other short-run determinants of respiratory health in a zip code, after conditioning on the total level number of active wells.

5. Results

5.1. Ordinary Least Squares Results

Table 4 presents the ordinary least squares (OLS) results from estimating Eq. (3) while controlling for the total number of active wells in the geographic region. The four columns correspond to estimation for zip codes within the specified distance from an active well during the sample period. The four geographic ranges considered are circles with a radius of 30, 60, 90, and 120 miles. Focusing on zip codes within 30 miles of an active well in Column (1), the coefficient of interest is the log of upwind flared natural gas from a zip code with a value of 0.0025. The interpretation of this coefficient is as follows: other things equal - a 1% increase in the amount of flared natural gas exposure will increase the hospital visitation rate by 0.000025, or one additional visit per month for a zip code with a population of 40,000. For all four ranges the coefficient is positive, but not statistically significant. We attribute this lack of statistical significance to the presence of endogeneity as discussed in Section 4. Specifically, the trend of younger, healthier individuals moving to the Bakken region as flaring increases (as seen in Fig. 7b), combined with the pattern of those individuals locating in areas with high levels of flaring (as seen in Panel C of Table 2), biases these OLS coefficients downward. This preliminary

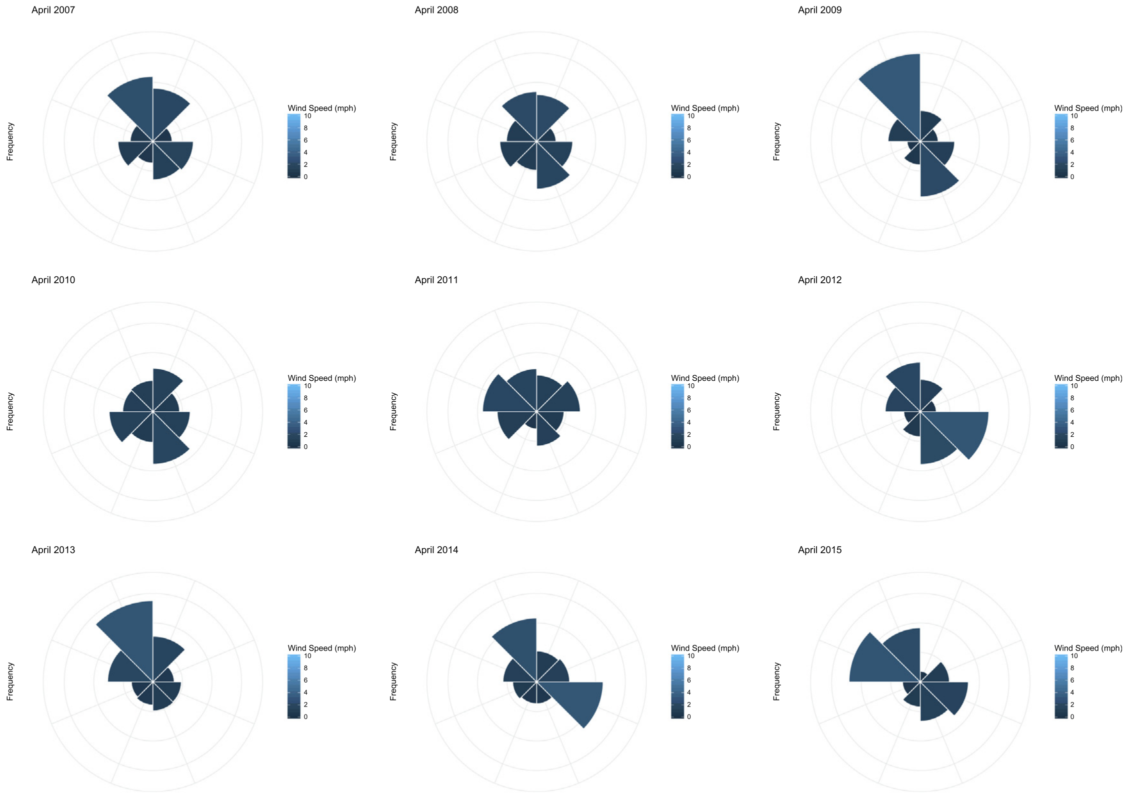
April 2007 April 2008 April 2009 April 2010 April 2011 April 2012 April 2013 April 2014 April 2015

Fig. 10. Frequency of Time the Wind Blew from and the Average Speed in Each Octant for April 2007–2015.

Table 4
OLS Estimates of Impact on Respiratory Health.

	(1) 30 Miles b/se	(2) 60 Miles b/se	(3) 90 Miles b/se	(4) 120 Miles b/se
Log(UpwindFlaring)	0.0025	0.0015	0.0014	0.0024
	(0.003)	(0.004)	(0.003)	(0.004)
Zip Code Fixed Effects	Y	Y	Y	Y
Month Fixed Effects	Y	Y	Y	Y
Active Well Control	Y	Y	Y	Y
Dep. var. mean	0.166	0.164	0.168	0.173
N	11,550	15,225	19,845	23,835

Notes: This table reports OLS regressions of the rate of respiratory-related hospital visits on upwind natural gas flaring for zip codes in North Dakota from 2007–2015. All specifications include the number of active wells in the region as a control. Standard errors are clustered at the zip code level. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level. **Sample:** Column (1) considers monthly observations from 110 zip codes that were within 30 miles of at least one active well during the sample period. Column (2) considers monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period. Column (3) considers monthly observations from 189 zip codes that were within 90 miles of at least one active well during the sample period. Column (4) considers monthly observations from 227 zip codes that were within 120 miles of at least one active well during the sample period.

OLS analysis demonstrates the necessity of our instrumental variables research design presented in the following subsection.

5.2. Instrumental Variables Analysis

5.2.1. First Stage Results

Panel A of Table 5 reports the first stage estimates, shown in Eq. (2) for the geographic ranges of 30, 60, 90, and 120 miles. Consistent with our instrumental variables design and discussion in Section 4.2, all specifications include the number of active wells in the region as a control. The impact of the number of wells connected to a constrained processing facility on the amount of natural gas flared is statistically significant for all geographic distances with the expected sign. This confirms our understanding of natural gas flaring in North Dakota: capacity constraints at processing facilities are a major determinant of the level of the flared natural gas from wells. The estimates in columns (1) to (4) of Table 5 indicate that a 1% increase in the number of upwind constrained wells from a zip code will result in a 0.05–0.11% increase in flared natural gas exposure. Across all four specifications, the first stage F statistic exceeds 10, which indicates that the number of wells connected to a constrained natural gas processing facility meets the criteria for a strong instrument outlined in Staiger and Stock (1994).

5.2.2. Second Stage Results

Panel B of Table 5 reports the second stage results. Column (1) reports the estimated effect of exposure to flaring from upwind wells within 30 miles on the zip code's respiratory-related hospital visitation rate. The estimated coefficient indicates that a 1% increase in exposure to flared natural gas will correspond to a 0.046 unit (0.28%) increase in respiratory-related hospital visitation rate for a zip code. Column (2) reports a similar estimate for

Table 5
IV Estimates of Impact on Respiratory Health for All Ranges.

	(1) 30 Miles b/se	(2) 60 Miles b/se	(3) 90 Miles b/se	(4) 120 Miles b/se
Panel A: First Stage				
Log(ConstrainedWells)	0.110^{***}	0.072^{***}	0.050^{***}	0.077^{***}
	(0.026)	(0.017)	(0.011)	(0.010)
Panel B: Second Stage				
Log(UpwindFlaring)	0.046^{*}	0.080^{**}	0.013	−0.038
	(0.027)	(0.039)	(0.046)	(0.030)
Zip Code Fixed Effects	Y	Y	Y	Y
Month Fixed Effects	Y	Y	Y	Y
Active Wells Control	Y	Y	Y	Y
Dep. var. mean	0.166	0.164	0.168	0.173
K.P. Wald F Stat	17.50	18.31	20.81	61.97
N	11,550	15,225	19,845	23,835

Notes: This table reports IV regressions of the rate of respiratory-related hospital visits on upwind natural gas flaring for zip codes in North Dakota from 2007–2015. Panel A corresponds to the first stage of the estimation, which uses the log of the number of wells connected to a constrained processing plant upwind from a zip code as an instrument for that zip code's exposure to flared natural gas. Panel B corresponds to the second stage estimates of the impact of flared natural gas on the rate of respiratory-related hospital visits in a zip code. All specifications include the number of active wells in the region as a control. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level. **Sample:** Column (1) considers monthly observations from 110 zip codes that were within 30 miles of at least one active well during the sample period. Column (2) considers monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period. Column (3) considers monthly observations from 189 zip codes that were within 90 miles of at least one active well during the sample period. Column (4) considers monthly observations from 227 zip codes that were within 120 miles of at least one active well during the sample period.

the effect of exposure to flaring from upwind wells within 60 miles of a zip code. In both of these cases, the results are statistically significant and greater than the OLS estimates. The IV estimates are an order of magnitude greater than the OLS estimates which is consistent with two endogeneity concerns in the OLS estimation: individual avoidance behavior (Neidell, 2009) and the migration of younger and healthier individuals to areas with oil activity (Cascio and Narayan, 2015).

Columns (3) and (4) of Panel B in Table 5 report the second stage estimates of the effect of exposure to flaring from 90 and 120 miles from a zip code. In both specifications, the estimated effect of upwind flaring is statistically indistinguishable from zero. This finding is consistent with Johnsen et al. (2019) who found the pollutants associated with natural gas flaring, but in the context of coal-fired generators, do not travel beyond 70 miles. Therefore, we focus on results for flaring within 30 and 60 miles of a zip code for the rest of this analysis.

Table 6 presents the IV results at the geographic ranges of 30 and 60 miles with an extensive set of control variables. Columns (1) and (4) add zip code demographic controls to the more parsimonious specification in Table 5. Columns (2) and (5) add controls for the number of active wells, oil extracted, and wells drilled both upwind and within range. The purpose of these additional controls is to account for all pollution sources from oil development activity near the zip code. Finally, columns (3) and (6), our preferred specifications, include both the demographic and production controls. The Kleibergen-Paap first stage Wald F statistics presented in Table 6 indicate that in all of these specifications, the instrument meets the criteria for being a strong instrument (Staiger and Stock, 1994). In addition, the relative stability of our coefficient of interest across the specifications in Tables 5 and 6 provides evidence that we have sufficiently controlled for economic and demographic factors that could impact respiratory health for a zip code.

Overall, the instrumental variables results in Tables 5 and 6 indicate that upwind flared natural gas has a significant effect on the respiratory health of individuals who reside within 60 miles of flaring wells. We examine the robustness of these results, an alternative difference-in-differences identification strategy, and a number of falsification tests that examine the validity of our research design in Section 5.3. In the following subsection we consider an expanded set of health related outcomes that could be impacted by exposure to flared natural gas. We then use these estimates to perform back of the envelope calculations for the change in health costs from reduced flaring if the 2018 standards of the North Dakota flaring policy had been implemented during our sample time period.

5.2.3. Additional Outcomes

Although in our main specifications we focus on all respiratory-related hospitalizations, this may not adequately capture the full range of medical costs related to flaring. Therefore, we estimate Eq. 3 for a number of alternative sub-populations and outcomes. Columns (1) and (2) of Table 7 report the results for our primary 60 mile analysis by type of respiratory hospitalization, emergency room (ER) or non-emergency room (Non-ER). The impact of exposure to flared natural gas is positive and statistically significant for respiratory-related emergency visits. The effect is positive but smaller and not statistically significant impact for non-emergency respiratory-related hospital visits.

Next, we examine the respiratory health of infants and the elderly. Infant health has been studied before in the context of UONGD (Hill, 2018; Cushing et al., 2020) and a recent survey of the health literature by Currie et al. (2014) notes that focusing on infant health has a number of advantages in terms of identification since infants have a shorter possible lifetime exposure period and limited geographic mobility. Although it is still possible for the parents of infants sensitive to air pollution to engage in avoidance behavior. Column (3) of Table 7 reports the results of our preferred specification when considering the percentage of all infant hospital visits that are respiratory-related visits (those with a primary Major Diagnostic Category code of four) from a zip code.[11] We expand the definition of respiratory-related hospital visits for these specifications because it is not necessary to distinguish between short term and long term respiratory-related issues for infants. The ICD-9 codes used in our primary analysis and analysis of elderly individuals ensures the respiratory-related visit observed was due to an external agent and due to a chronic condition. The estimate is positive and statistically significant, which confirms the understanding in the literature that flared natural gas has an adverse impact on infant health. Column (4) of Table 7 reports the results of our preferred specification for respiratory-related hospital visits by those

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[11] We use the percentage of all infant visits that are respiratory-related due to a lack of infant population data for zip codes.

Table 6
Primary IV Results of Impact on Respiratory Health.

	30 Miles			60 Miles		
	(1) b/se	(2) b/se	(3) b/se	(4) b/se	(5) b/se	(6) b/se
Panel A: First Stage						
Log(ConstrainedWells)	0.105^{***}	0.098^{***}	0.094^{***}	0.072^{***}	0.055^{***}	0.056^{***}
	(0.026)	(0.018)	(0.018)	(0.017)	(0.014)	(0.014)
Panel B: Second Stage						
Log(UpwindFlaring)	0.053^{*}	0.052^{*}	0.061^{**}	0.085^{**}	0.113^{**}	0.120^{**}
	(0.028)	(0.030)	(0.030)	(0.040)	(0.051)	(0.050)
Zip Code Fixed Effects	Y	Y	Y	Y	Y	Y
Month Fixed Effects	Y	Y	Y	Y	Y	Y
Active Wells Controls	Y	Y	Y	Y	Y	Y
Production Controls	-	Y	Y	-	Y	Y
Demographic Controls	Y	-	Y	Y	-	Y
Dep. var. mean	0.166	0.166	0.166	0.164	0.164	0.164
K.P. Wald F Statistic	16.35	28.40	27.65	18.16	14.60	15.50
N	11,550	11,550	11,550	15,225	15,225	15,225

Notes: This table reports IV regressions of the rate of respiratory-related hospital visits on upwind natural gas flaring for zip codes in North Dakota from 2007–2015. Panel A corresponds to the first stage of the estimation, which uses the log of the number of wells connected to a constrained processing plant upwind from a zip code as an instrument for that zip code's exposure to flared natural gas. K.P. refers to the Kleibergen-Paap first stage Wald F statistic. Panel B corresponds to the second stage estimates of the impact of flared natural gas on the rate of respiratory-related hospital visits in a zip code. Columns (1), (3), (4), and (6) add controls for the average house size, value, and income for the zip code. Columns (2), (3), (5), and (6) add total oil extracted upwind, oil extracted within range, the number of upwind wells drilled, total wells drilled within the specified range, and total upwind wells of the zip code as additional controls. Standard errors are clustered at the zip code level. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level. **Sample:** Columns (1) - (3) consider monthly observations from 110 zip codes that were within 30 miles of at least one active well during the sample period. Columns (4) - (6) consider monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period.

Table 7
IV Estimation: Alternate Outcomes.

	IV Estimation							IV-Tobit	
	Lung Visits		Age		All Hospitalizations			Mortality	
	ER	Non-ER	<1	$\geqslant 65$	All Visits	ER	Non-ER	$\geqslant 65$	$\geqslant 65$
	(1) b/se	(2) b/se	(3) b/se	(4) b/se	(5) b/se	(6) b/se	(7) b/se	(8) b/se	(9) b/se
Log(UpwindFlaring)	0.083^{**}	0.037	2.424^{*}	0.079^{**}	0.284^{**}	0.236^{***}	0.047	0.304^{***}	0.059
	(0.037)	(0.035)	(1.299)	(0.032)	(0.118)	(0.078)	(0.109)	(0.061)	(0.13)
Area FEs	Y	Y	Y	Y	Y	Y	Y	-	Y
Month FEs	Y	Y	Y	Y	Y	Y	Y	Y	Y
Wells Control	Y	Y	Y	Y	Y	Y	Y	Y	Y
ACS Controls	Y	Y	Y	Y	Y	Y	Y	-	-
Other Controls	Y	Y	Y	Y	Y	Y	Y	-	-
Dep. var. avg.	0.060	0.104	1.101	0.103	0.785	0.191	0.594	0.456	0.456
N	15,225	15,225	15,225	15,225	15,225	15,225	15,225	945	945

Notes: This table reports IV regressions of various outcomes on upwind natural gas flaring to examine the robustness of our main results. Columns (1) and (2) provide estimates of the impact for the rate of emergency (ER) and non emergency respiratory-related visits for a zip code. Column (3) shows the percentage of all respiratory-related infant hospital visits per zip code. Column (4) considers the rate of respiratory-related hospital visits for those over 65 for a zip code. Columns (5) - (7) examine the outcome of the rate of all hospitalizations, ER hospitalizations, and non-ER hospitalizations for a zip code. Columns (8) and (9) provide county level estimates of the impact of flared natural gas on the mortality rate for those over 65 using an IV tobit framework. All specifications include the number of active wells as a control. All specifications in columns (1) to (7) include controls for oil extracted, and wells drilled both upwind and total within the specified range of the zip code, along with average house size, value, and income as additional controls. Standard errors are clustered at the zip code level in columns (1) to (7) and are White-Huber or Heteroskedastic consistent standard errors for the specifications in columns (8) and (9). *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level. **Sample:** Columns (1) - (7) consider monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period. Columns (8) - (9) consider monthly observations from 9 counties that were within 60 miles of at least one active well during the sample period and had at least one non-bottom coded mortality observation.

over 65. Results are positive and statistically significant, indicating that flaring has an adverse impact on respiratory health for this more geographically mobile group. These results provide additional evidence that our primary results are not likely to be explained by residential sorting and that the adverse health impacts of flaring are not restricted to a single age group.

Motivated by our finding that flaring has a large negative impact on the respiratory health of elderly individuals. We use publicly available mortality data at the county level and data on the number of individuals over 65 who reside in a county to investigate the impact of flaring on mortality. Consistent with the bottom coding of this data, which omits county-month observations with less than 10 deaths, we estimate Eq. 3 as a censored IV Tobit. Columns (8) and (9) of Table 7 report the results of this analysis for the limited county-month level sample. While the statistical significance and magnitude of these results is sensitive to the inclusion of county level fixed effects, the limited results in column (9) indicate that a 1% increase in exposure to flared natural gas is associated with a 0.13% increase in elderly mortality. Although this association is large relative to recent estimates on the impact of particulate matter on mortality,[12] this may be attributed to other pollutants associated with flaring. Overall, these results indicates that flaring may have substantial mortality related costs and that further investigation is warranted.

Finally, we explore the sensitivity of our results to the choice of respiratory-related hospital visits as the outcome variable of interest. Previous studies have found an association between air pollution and a number of outcomes beyond respiratory health. These include infant mortality, cardiovascular health, and other cancers

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[12] Deryugina et al. (2019) find that a 1% increase in particulate matter corresponds with a 0.0178% increase in elderly mortality.

(Schlenker and Walker, 2015; Currie et al., 2009). Given the rarity of these outcomes and the limited size of our population, we instead focus on the aggregate rate of hospital visits with the understanding that it will reflect the accumulation of these additional health outcomes from flared natural gas. Columns (5), (6), and (7) report the results of our preferred specification for the rate of all visits, all ER visits and all non-emergency room hospital visits from a zip code. The effects are positive and statistically significant for both all visits and ER visits.

5.3. Alternative Identification, Robustness, and Falsification Tests

We believe that our instrumental variables analysis provides strong evidence in support of a causal link between flared natural gas and health. However, to provide additional evidence of this causal link, we examine the robustness of our main results. First, we examine whether our results are driven by our instrumental variables research design by estimating both a difference-in-differences and a synthetic control model based on the North Dakota flaring policy. Next, we examine our research design by performing a series of falsification tests. Finally, we describe a variety of additional sensitivity analysis of our instrumental variables design to choices regarding functional form and variable construction that is provided in the appendix.

5.3.1. Difference-in-Differences and Synthetic Controls

As an alternative specification, we consider a difference-in-differences identification strategy that exploits variation in the effect of the North Dakota flaring policy. Specifically, we compare zip codes that were in the second and fifth quintile of total natural gas extracted from wells within 60 miles of the zip code centroid in October 2013, when initial planning for the policy was announced. Zip codes in the fifth quintile should experience a significant drop in flaring after policy implementation, while zip codes in the second quintile should experience relatively little change in their exposure to flared natural gas. The time frame considered for this difference-in-differences analysis stretches from the initial announcement of the policy in October 2013 to the end of our sample data in September 2015, the 12 months prior to and following implementation in October 2014.

There are a number of advantages with using this difference-in-differences design to estimate the causal impact of the policy on reducing respiratory hospitalizations through a reduction in flaring. First, by focusing on only the 12 months prior to and following the policy, we lessen the extent to which long term upward trend in flaring exposure observed in Fig. 6 may lead to differential trends in respiratory hospitalization between treated and control groups. Over a single year, the majority of variation in flaring exposure for the treated group is likely driven by varying wind patterns across months, rather than differential changes in shale development activity. Second, due to their close proximity to the economic activity from nearby shale development, control zip codes in the second quintile of nearby gas extraction when the policy was announced likely have similar population demographics and exposure to other sources of pollution as fifth quintile treated zip codes. The large number of contemporaneous factors that impact respiratory health, combined with the narrow time frame considered, lends credibility to the idea that these control zip codes will reflect the trend in respiratory hospitalizations for treated zip codes in the absence of the policy. Thereby satisfying the parallel trends assumption.

Finally, relative to our main instrumental variables-based identification strategy, this alternative difference-in-differences strategy is not subject to the same concerns regarding unobservables related to both respiratory health and upwind constrained well activity. For example, if driving routes for oil trucks change in response to abnormal wind patterns or limited natural gas processing capacity, then using the number of upwind constrained wells as an instrument for flaring might lead us to wrongfully associate the health effects from vehicle pollution to flaring. Although such a scenario is relatively unlikely, it would not be a concern for the difference-in-differences based strategy. Under the policy, firms must capture a fixed percentage of the natural gas produced across all of their wells. Effectively, a firm has the same incentive to reduce flaring at wells where there is only a small amount of activity, the control areas, as they do at wells in areas with high amounts of flaring, the treated areas. Therefore, the incentive to reduce flaring at wells is independent of changes in local gas processing capacity or abnormal wind patterns.

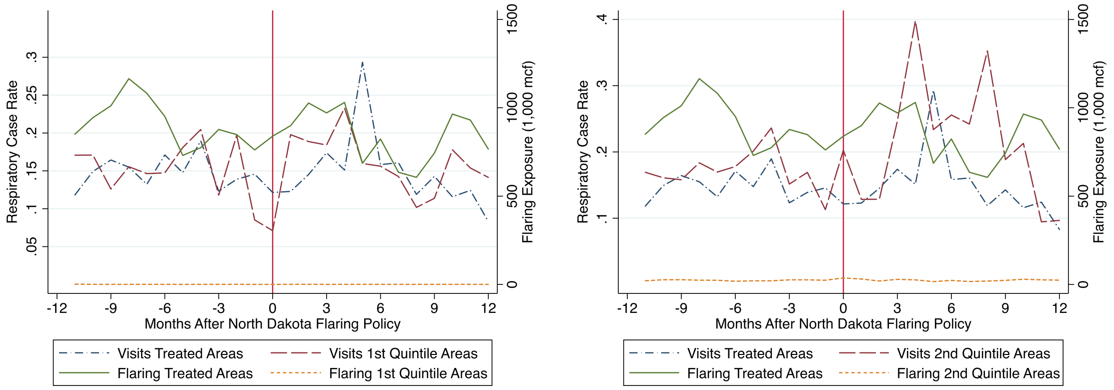
Our econometric specification for this difference-in-differences analysis is:

$$Health_{it} = \beta_0 + \beta_1 \cdot Treated_{it} + \gamma_i + \delta_t + \varepsilon_{it}.$$

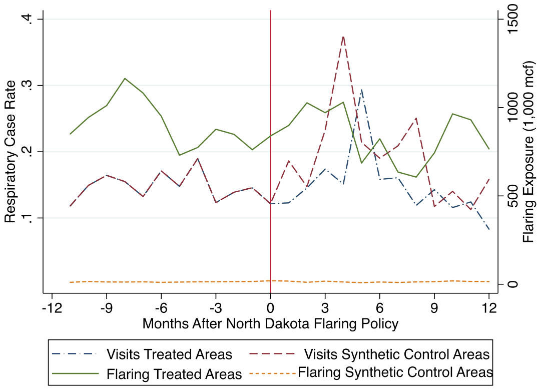
Treated takes a value of one if the month is in the post policy time period (post September 2014) and the zip code was in the fifth quintile of total natural gas extracted from wells within 60 miles at the time of the policy announcement (October 2013). Figs. 11a and b present the respiratory-related hospital visitation rate and flaring exposure for this treated group as well as the first and second quintile control groups, respectively. Prior to implementation, treated and control zip codes follow a similar trend in their respiratory-related hospital visit rate, providing evidence that the identifying assumption of parallel trends in the post treatment time period is satisfied. Following implementation of the policy, control zip codes experienced little to no change in their exposure to flared natural gas and a moderate increase in their hospitalization rate, likely due to an increase in other factors which influence respiratory health, such as vehicle traffic. In contrast, treated zip codes experienced both a decline in their exposure to upwind flared natural gas and little change in their rate of respiratory hospitalizations. Assuming the parallel trends assumption holds, this indicates that in the absence of the policy, respiratory hospitalizations would have increased for treated zip codes. The decrease in respiratory hospitalizations from reduced exposure to flared natural gas for treated zip codes mitigated the counterfactual increasing trend in hospitalizations exhibited by control zip codes.

Columns (1) to (6) of Table 8 present the corresponding regression results for this first difference-in-differences analysis, with all specifications indicating a negative effect of the flaring policy on zip codes with high levels of natural gas extraction activity within 60 miles. Columns (1) - (2) present a comparison between the fifth and first quintiles, a group with less proximity to overall extraction, but also less susceptible to changes in flaring exposure. Columns (3) - (4) present a comparison between the fifth and second quintile; the estimated treatment effect using the full set of controls in column (4) is statistically significant at the 5% level. Columns (5) - (6) show the results when using both the first and second quintiles as the control group; only the treatment effect with the full set of controls, in column (6), is statistically significant at the 10% level.

Given the importance of satisfying the parallel trends assumption in a difference-in-differences setting, we utilize a synthetic control methodology to formulate a control group that more closely matches the treated zip codes' trend in respiratory-related hospital visitation rate prior to the policy taking effect. We use the framework of Robbins et al. (2017) to draw sample weights for control zip codes in the first and second quintile. Specifically, the weights are selected by minimizing the total sum of squared weights across potential control zip codes subject to two constraints 1) the total sum of weights across control zip codes must equal the total number of treated zip codes (29) and 2) the weighted control group hospitalization rate must equal the treated



(a) Unweighted control (first quintile) (b) Unweighted control using (second quintile)



(c) Synthetic control

Fig. 11. Flaring and Respiratory Visits Before and After Policy Implementation.

Table 8
Alternate Identification: Impact of the Flaring Policy on Respiratory Health.

	Difference-in-Differences						Synthetic Control		
	vs. 1st		vs. 2nd		vs. 1st & 2nd		vs. 1st	vs. 2nd	vs. 1st&2nd
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se
Treated	−0.021*	−0.020	−0.053*	−0.103**	−0.036	−0.066*	−0.029*	−0.093*	−0.048**
	(0.012)	(0.013)	(0.031)	(0.049)	(0.026)	(0.034)	(0.017)	(0.049)	(0.021)
Zip Code FEs	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month FEs	Y	Y	Y	Y	Y	Y	Y	Y	Y
Controls	–	Y	–	Y	–	Y	–	–	–
Dep. var. avg.	0.153	0.153	0.174	0.174	0.168	0.168	0.177	0.242	0.198
N	1,392	1,392	1,392	1,392	2,088	2,088	1,392	1,392	2,088
Largest Weight	-	-	-	-	-	-	2.99	2.78	1.35
# Weights > 0	-	-	-	-	-	-	25	21	56

Notes: This table reports differences-in-differences and synthetic control regressions that measure the impact of exposure to flared natural gas on the respiratory-related hospital visitation rate for zip codes in North Dakota from 2013–2015. For each specification, treatment timing is identical, October 2014, with zip codes in the top quintile of natural gas extracted within the geographic range at the time of the policy announcement in October 2013 defined as being in the treated group. For columns (1) to (6) standard errors are clustered at the zip code level. For columns (7) to (9) standard errors are derived from 500 jackknife permutations, consistent with the literature on synthetic control (Robbins et al., 2017). Specifications in columns (2), (4), and (6) include both the number of active wells, oil extracted, and wells drilled both upwind and total within the specified range of the zip code, along with average house size, value, and income as additional controls.*** indicates significance at the 1% level, ** at the 5% level, * at the 10% level. **Sample:** Columns (1), (2), and (6) consider the zip codes in the first and fifth quintile of flared gas exposure from wells within 60 miles of the zip code centroid in October 2013. Columns (3), (4), and (7) consider the zip codes in the second and fifth quintile of flared gas exposure from wells within 60 miles of the zip code centroid in October 2013. Columns (5), (6), and (9) consider the zip codes in the first, second, and fifth quintile of flared gas exposure from wells within 60 miles of the zip code centroid in October 2013. Column (7) selects a synthetic control group by assigning positive weight to 25 of the 29 zip codes in the first quintile. Column (8) selects a synthetic control group by assigning positive weight to 21 of the 29 zip codes in the second quintile. Column (9) selects a synthetic control group by assigning positive weight to 56 of the 58 zip codes in the first and second quintile. The time period considered is October 2013 to October 2015.

group hospitalization rate in each of the 12 pre-treatment months. The corresponding estimated treatment effect of the policy is the difference between the per period average hospitalization rate of treated zip codes and the per period synthetic weighted average hospitalization rate of control zip codes over the 12 post-treatment months. Standard errors are obtained by taking the variance of the treatment effect estimates across 500 jackknife permutation groups. By selecting a synthetic control group based only on matching pre-treatment hospitalization, we assume the other associated factors that impact respiratory health will be equalized across treatment and control zip codes. Therefore, under this assumption, the observed change in hospitalizations in the post-treatment period for the synthetic control zip codes represents the contemporaneous change in hospitalizations for the treated zip codes in the absence of the policy.

Fig. 11c presents the effect of policy for the 12 months post-implementation, as well as the matched rate between treatment and control prior to implementation. Columns (7) to (9) of Table 8 show the corresponding results with jackknife permutation derived standard errors as well as the associated characteristics of the synthetic control group weights. The treatment effect of the policy on respiratory-related hospital visits for all three groups is negative and statistically significant. Scaling the respiratory treatment effect from column (9) and the change in flaring exposure by treated zip codes (62,800 mcf) to the 60 mile range averages for respiratory visitation and upwind flaring in Table 2. We calculate that the policy corresponds with a 29.27% reduction in hospitalizations and a 47.4% reduction in flaring. This implies that a 1% reduction in flaring would lead to a 0.62% reduction in hospitalization, which is comparable to the effect we estimate using our instrumental variables specification in Table 6.

Overall, the results of these alternative difference-in-differences analyses are consistent with our primary result that exposure to upwind flared natural gas increases the respiratory-related hospital visitation rate. Furthermore, these alternative estimation strategies indicate that our primary results are not an artifact of our instrumental variables estimation strategy.

5.3.2. Falsification Tests

Identification in this study hinges on the assumption that, conditional on controlling for local oil-related economic activity and demographics, the number of upwind wells from a zip code that are connected to a constrained facility is as good as randomly assigned. There are two ways in which this assumption could fail. One is if there are still changes in population demographics that correspond with the variation in the number of constrained upwind wells. In practice, this would result in our estimation strategy predicting health outcomes associated with different population groups that are unrelated to air pollution. The second is if the number of upwind wells connected to a constrained processing facility, conditional on our controls for oil development, still predict increases in other sources of air pollution. Previous work has indicated that oil development in North Dakota has led to increases in vehicle traffic (Fershee, 2012), thus reducing local air quality (Knittel et al., 2016). Therefore, it is important to examine our primary result with a robust set of controls regarding local UONGD, as well as to test our empirical framework with an outcome associated with non-flaring sources of emissions. Similar to Schlenker and Walker (2015), we use broken bones (trauma), appendicitis, and strokes as false outcomes in addition to hospitalizations associated with vehicle accidents. Although these outcomes occur less frequently than respiratory hospitalizations, we feel that there is significant variation to perform a useful falsification analysis in our setting.

Table 9 presents 2SLS results for estimating Eq. 3 with these outcomes that should be unrelated to exposure to flared natural gas if our research design is valid. Columns (1) and (5) estimate our preferred 2SLS specification in which the dependent variable is a zip code's vehicle-related hospital visitation rate. The estimates for both geographic ranges are not statistically significant at conventional levels. This indicates that there is no evidence that our measure of exposure to flared natural gas corresponds to increased vehicle traffic. Columns (2) and (6) report estimates from our preferred specification using a zip code's rate of appendicitis related hospital visits as the outcome variable. Appendicitis is more likely to occur for individuals between 13 and 40 years of age (Körner et al., 1997), and is not influenced by air pollution. The value of examining this outcome is that any increases would be associated with a younger and healthier population, moving to areas with high levels of oil-related activity. The coefficients for appendicitis are statistically insignificant, providing evidence that our main results are not simply driven by demographic changes in the population. Columns (3) and (7) report point estimates using the rate of trauma-related hospital visits for a zip code, a health outcome that should be completely unrelated to exposure to flared natural gas, but would correspond to a trend toward riskier activities in the population. Finally, columns (4) and (8) report point estimates using the rate of stroke-related hospital visits for a zip code, another health outcome that is not considered to be impacted by air pollution according to the literature (Schlenker and Walker, 2015).[13] In all cases, we fail to reject the null hypothesis that our research design is not picking up health trends unrelated to air pollution from flared natural gas.

5.3.3. Additional Analysis

We provide additional results regarding falsification tests and the robustness of our main result in the appendix. These appendix analyses include (i) testing the importance of the functional form by estimating a Poisson regression, (ii) testing the statistical significance of the main IV results using heteroskedastic consistent standard errors and standard errors clustered at the county level, (iii) examining the importance of zip code specific health trends by estimating our primary model with zip code time trends, (iv) examining the importance of being downwind from recently drilled wells, (v) testing for whether the respiratory health effect is the result of cumulative exposure to flared natural gas or contemporaneous exposure to flared natural gas, (vi) testing for the consistency of the main result with both leads and lags of monthly exposure to flared natural gas, (vii) testing the sensitivity of the main results to the definition of a constrained natural gas plant, (viii) testing the sensitivity of results to the definition of the outcome variable by estimating a log–log specification, and (ix) testing our primary specification on a population of less healthy individuals observed in our hospital data both prior to and after 2010. The robustness of our results under these alternative specifications confirm both the nature of our primary result and the validity of our research design.

6. Economic Costs and the Distribution of Damages

6.1. Economic Costs: Back of the Envelope Calculation

We now use our regression estimates to calculate a lower bound on reduced social costs from current U.S. flaring reduction policy. Specifically, we consider the associated health costs that could have been avoided if the 2018 flaring standards of the North Dakota flaring policy were in place at the beginning of our sample period. We first calculate that under the 2018 mandated 88% capture rate, the amount of flared natural gas would have been reduced by 310 million thousand cubic feet (mcf) or 56.2% if the total amount of gas produced during our sample time frame remained constant.[14] We then compute the corresponding reduction in respiratory-related hospital visits using the estimates from column (6) of Table 6. Our estimates suggest that the number of respiratory-related visits would have decrease by 11,887 (33%).[15]

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[13] We use the following ICD-9 codes for each of these outcomes. Vehicle Accidents are E810 - E829 and E846 - E849. Stroke are 430–434. Trauma (broken bones) are 800–829. Appendicitis are 540–543

[14] In reality only 72.6% of all gas produced was captured during the sample period.

[15] Since this is a level-log specification a $p\%$ change in flaring corresponds to a $\hat{\beta}_1 \cdot log(1 + p/100)$ level change in the hospital visitation rate.

Table 9
IV Results: Falsification Tests.

	30 Miles				60 Miles			
	(1) Vehicle Rate	(2) Appendix Rate	(3) Trauma Rate	(4) Stroke Rate	(5) Vehicle Rate	(6) Appendix Rate	(7) Trauma Rate	(8) Stroke Rate
Log(UpwindFlaring)	0.0088	−0.0012	0.0118	0.0011	0.0143	−0.0071	0.0105	0.0031
	(0.0079)	(0.0039)	(0.0093)	(0.0106)	(0.0110)	(0.0048)	(0.0129)	(0.0215)
Zip Code Fixed Effects	Y	Y	Y	Y	Y	Y	Y	Y
Month Fixed Effects	Y	Y	Y	Y	Y	Y	Y	Y
Active Wells Controls	Y	Y	Y	Y	Y	Y	Y	Y
Oil Production Controls	Y	Y	Y	Y	Y	Y	Y	Y
Demographic Controls	Y	Y	Y	Y	Y	Y	Y	Y
Dep. var. mean	0.0286	0.0058	0.0388	0.0213	0.0281	0.0059	0.0377	0.0231
N	11,550	11,550	11,550	11,550	15,225	15,225	15,225	15,225

Notes:). This table reports IV results of various falsification tests of our primary analysis using alternative outcomes. Columns (1) and (5) show results for the rate of vehicle related hospital visits per zip code. Columns (2) and (6) show results for the rate of appendicitis related hospital visits per zip code. Columns (3) and (7) show results for the rate of trauma related hospital visits per zip code. Columns (4) and (8) show results for the rate of stroke related hospital visits per zip code. All specifications include the number of active wells, oil extracted, and wells drilled both upwind and total within the specified range of the zip code, along with average house size, value, and income as additional controls. Standard errors are clustered at the zip code level.*** indicates significance at the 1% level, ** at the 5% level, * at the 10% level. **Sample:** Columns (1) to (4) consider monthly observations from 110 zip codes that were within 30 miles of at least one active well during the sample period. Columns (5) to (8) consider monthly observations from 145 zip codes that were within 60 miles of at least one active well during the sample period.

Next, we translate this to 2018 dollars by combining the average observed charge for a respiratory-related hospital visit in our data, $28,919 with the estimated $8,379 associated earnings reduction from a hospitalization according to Dobkin et al. (2018).[16] Combining these estimates, an 88% capture rate during our sample time period would have reduced associated costs from respiratory hospitalizations by $443.35 million or roughly $49.26 million per year. The total cost is similar in magnitude to the engineering based estimates in Section 2.3.

For comparison to other settings, these numbers are equivalent to having the associated hospitalization costs of flaring be $1.43 per mcf for an area with a population density of 6.2 people per square mile. This amount is large relative to both the average industrial price of natural gas during our sample period, $5.34 per mcf, as well as the $2.19 per mcf external climate cost from flaring discussed in Agerton et al. (2020). Furthermore, our annual estimate of $49.26 million is 7.7% of the annualized expenditures oil and gas producers spent on gas gathering and well connections during the implementation of the North Dakota flaring policy (Lade and Rudik, 2020). Since it would have been profitable for many of these wells to connect to gas processing infrastructure in the absence of the regulation, 7.7% is a lower bound on the percentage comparison of the health costs to the additional connection costs from the policy.

We believe our estimates are a conservative lower bound for the associated medical costs of flaring for a number of reasons. First, our cost estimates do not consider flaring's impact on other types of hospitalizations nor mortalities. If we repeat the same calculations above using the estimate for all hospitalizations from column (5) of Table 7, the 88% capture rate would have reduced medical costs from all hospitalizations during our sample period by $853.33 million or $94.81 million annually. Additionally, recent work demonstrating that pollution has an impact on cognition would indicate that the pollutants from flaring may impact learning (Currie et al., 2014). Third, our estimates only capture the respiratory health costs of those who are hospitalized, so costs associated with doctor visits or lost wages associated with sick leave spent at home are not captured.

Our associated hospitalization cost estimates, combined with the social cost of carbon, and the cost of other associated pollutants such as light pollution (Boslett et al., 2021), indicate that the benefits of flaring reduction policies are economically significant. However, restrictions on flaring impose costly trade offs for oil producers. In studying the mechanisms through which producers complied with the North Dakota flaring policy, Lade and Rudik (2020) find that wells were completed and connected to gas infrastructure more quickly. Additionally, they find that firms curtailed oil and gas production. Although it is not explicitly examined in their study, one may be concerned that the incentive to quickly connect a well may reduce the bargaining position of well operators with midstream firms, causing them to enter into less profitable gas gathering agreements.[17] Agerton et al. (2020) also discuss how heterogeneity in connection costs for wells, ranging from $0.45 per mcf to over $100 per mcf, depend on a well's location. These results indicate that restrictions on flaring may reduce the number of wells drilled or induce firms to shift production to areas with lower gathering costs. For some wells, the combined profit from oil and gas production may not exceed the high gathering line connection cost. Additionally, they state that "further work on appropriately quantifying social costs and benefits of flaring will improve the ability of policy makers to set policies in a way that improve social welfare." Given the possibility that under certain conditions, the reduction in oil production from flaring restrictions may be greater than the socially optimal reduction. Although we consider the quantification of the costs borne by producers from restrictions on flaring to be beyond the scope of this analysis, it is a potential avenue for future research.

6.2. Geographic Distribution of Damages

The literature on the welfare consequences of shale development is concerned with heterogeneity in the benefits for the local population (Bartik et al., 2019), while the literature on environmental inequity often considers inequality in exposure to various pollutants (Boyce et al., 2016). In this section, we ask whether the areas with the highest levels of extracted oil revenue also experienced the highest levels of exposure to flared natural gas.

Fig. 12 displays the disparity between extracted oil revenues and exposure to pollution from flaring for the geographic ranges of 30 and 60 miles. Zip code oil revenue is defined as the total

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[16] The $28,919 average charge is comparable to the literature, particularly Pfuntner et al. (2006) who put the cost of a respiratory-related hospital stay at $25,422 in 2018 dollars.

[17] Recently there has been litigation by operators who would rather choose to flare than sell since the negotiated tariff for processing exceed the value of the gas (Holland, 2019).

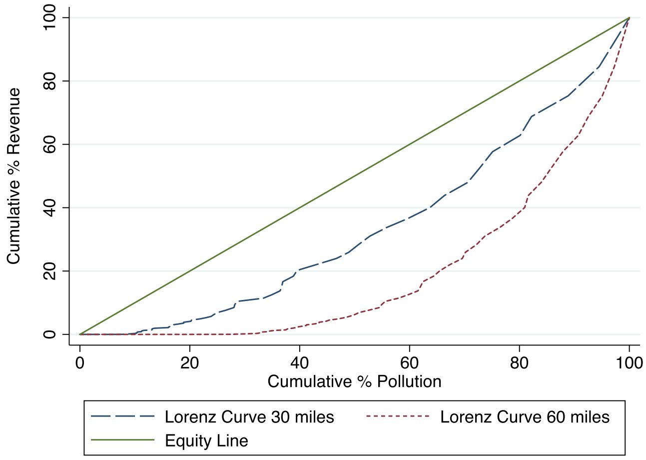

Fig. 12. Inequality in the Distribution of Pollution from Flaring.

amount of oil extracted from wells within the zip code multiplied by the monthly oil price, over the sample period. [18] The percentage of revenue is then determined by dividing the total revenue for a zip code by the combined sum of revenue across all sample zip codes. A zip code's proportion of pollution is defined in a similar manner, where pollution is exposure to upwind flared natural gas during the sample period.

Results from Fig. 12 indicate a modest amount of inequality in exposure to flared natural gas at a range of 30 miles with a Gini coefficient value of 0.503. This measure of exposure inequality increases to 0.724 once we expand the geographic range to include zip codes that were within 60 miles of an active well at any time during the sample period. [19] Focusing on the least productive zip codes, that combined to extract 20% of the oil revenues during the sample period, this group was exposed to more than 38.9% of the total upwind flared at a range of 30 miles and 64.3% of the total at a range of 60 miles. Moreover, using the average observed costs for a respiratory-related hospital visit and our preferred IV estimates (Column 6 of Table 6), we find that the estimated reduction in health costs under the 88% capture rate of the North Dakota flaring policy exceeds the oil revenues for 50.4% of zip codes at a range of 60 miles. Therefore, there is evidence that many zip codes exposed to flared natural gas did not extract significant amounts of oil during the sample period.

Next, we investigate who are the associated "winners" with oil production in the Bakken. Specifically, we regress demographic and employment characteristics on zip code flaring exposure. We consider both the log of cumulative flared natural gas exposure, controlling for local oil extraction, as well as the log of flared gas exposure per dollar of extracted oil.[20] As we show in Panel A of Table 10, zip codes with higher levels of exposure to flared natural gas tend to have lower levels of employment, lower incomes, and a greater proportion of people of color.[21] Similarly, Panel B of Table 10 indicates that the zip codes with higher exposure per dollar of extracted oil had lower incomes, lower levels of employment, and a greater proportion of people of color. Overall, these results suggest that during the oil boom in North Dakota, low-income communities and people of color were more likely to be exposed to the damages from UONGD, while receiving fewer associated benefits.

There are a number of caveats to these analyses. First, for the analysis of oil revenues versus flaring exposure, there is significant variation in oil prices across wells in North Dakota that could impact our revenue estimates. However, we obtain similar results if we restrict our analysis to the distribution of oil barrels extracted. Second, due to high rates of absentee mineral ownership in the Bakken, there is no guarantee that the residents of a zip code that extracts a significant amount of oil receive substantial benefits (Brown et al., 2019); royalties may be distributed outside the zip code. Third, the analysis of the demographic and income characteristics of zip codes disproportionately exposed to flared natural gas is merely descriptive. It does not shed light on the mechanisms driving the pattern of higher exposure, such as selection based on willingness to pay or firms disproportionately choosing to locate wells near communities with less political power. Therefore, the socioeconomic analysis only shows a disparity in geographic flaring exposure and oil extraction, and provides descriptive characteristics of the communities subject to this disparity. Nonetheless, these analyses are informative because the value of the oil extracted represents a reasonable estimate of the local benefits from resource development and for many areas this value is less than the estimated health costs from flaring exposure. Therefore inequities in royalties and health costs may warrant a more comprehensive analysis in future studies.

7. Conclusion

The primary contribution of this paper is to identify a causal relationship between flared natural gas exposure and respiratory health. To our knowledge, this is the first paper to document a causal relationship between exposure to flared natural gas from oil wells and changes in respiratory health. Our approach exploits variation in exposure to flared natural gas induced by naturally occurring changes in wind direction interacted with the constrainedness of upwind wells' natural gas processing capacity. In the quasi-experimental design, treatment is defined as a zip code being downwind from a well that is constrained in the amount of natural gas it can sell for processing. The analysis provides evidence of a causal link between the amount of flared natural gas up to 60 miles upwind from a zip code and the percent of that zip code's population that experiences a respiratory-related hospital visit within a given month.

The size of the estimated effect of flared natural gas exposure and respiratory health is substantial. In our preferred specification, a 1% increase in upwind flared natural gas within 60 miles leads to an increase of 0.73% in the zip code's respiratory-related hospital visitation rate for a given month. Alternative empirical strategies based on difference-in-differences and synthetic control methodology produce qualitatively similar results. If flaring had been reduced by 56% during our nine year sample period, to comply with North Dakota's flaring policy, the total number of respiratory-related hospital visits for individuals who live within 60 miles of an active oil well would decrease by 11,887 (33%). This translates to roughly $443 million in medical expenses or $1.43 per mcf flared, which is 65% of the external climate cost of natural gas flaring of $2.19 per mcf found in other studies. We consider these estimates a lower bound on the associated health costs from flaring. Supplementary results from our analysis indicate future research into flaring's impact on mortality and other types of hospitalizations is needed.

In addition, we contribute to the literatures on environmental justice and the distribution of welfare impacts from shale development. We document that a disproportionate share of the damages from flaring are concentrated in disadvantaged communities.

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[18] We use the monthly average price at the wellhead across North Dakota from the EIA's "First Purchase Prices by Area" data.

[19] The Gini coefficient lies in the interval between zero and one, with higher values denoting greater levels of inequality.

[20] We divide flared gas exposure by one plus the total value of oil extracted in the zip code since many exposed zip codes did not extract any oil.

[21] We construct the employment variable by using the ACS value for rate of employment for individuals between 20 and 64.

Table 10
Association Between Flaring Exposure and Demographic or Socioeconomic Characteristics.

	(1) % Black b/se	(2) % White b/se	(3) % Hispanic b/se	(4) Log(Income) b/se	(5) % Employed b/se
Panel A: OLS Analysis					
Log(Upwind Flaring)	0.065^{**}	-0.486^{**}	0.137^{***}	−0.001	−0.332
	(0.030)	(0.244)	(0.048)	(0.005)	(0.287)
Log(Local Oil Revenue)	-0.086^{*}	0.272^{*}	−0.069	0.011	1.081^{***}
	(0.048)	(0.621)	(0.084)	(0.007)	(0.399)
Panel B: OLS Analysis					
Log(Exposure per 100,000 oil$)	0.001	-0.056^{*}	0.006^{*}	-0.0005^{**}	-0.029^{***}
	(0.001)	(0.029)	(0.003)	(0.0002)	(0.011)
Dep. var. mean	0.462	91.273	1.874	10.216	75.751
N	145	145	145	145	145

Notes: This table reports OLS regressions of zip code socioeconomic and demographic characteristics on cumulative exposure to upwind natural gas flaring. Panel A considers both the log of cumulative exposure to upwind flared natural gas and the log of cumulative oil revenues for a zip code as independent variables. Panel B considers the log of exposure per $100,000 in cumulative oil revenues plus one as the independent variable of interest. Standard errors are White-Huber or Heteroskedastic consistent standard errors. Column (1) considers the percentage of the population that is black. Column (2) considers the percentage of the population that is white. Column (3) considers the percentage of the population that is Hispanic. Column (4) considers the log of the average median income. Column (5) considers the percentage of the population between 20 and 64 that is employed. There are no other controls or fixed effects in these regressions. All percentage outcome variables are from 0 to 100. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level. **Sample:** In all specifications, we consider the 145 zip codes within 60 miles of an active well during the 2007–2015 sample period. All exposure and revenue variables are based on this 2007–2015 time period. Due to a lack of some variables in earlier ACS datasets, demographic and socioeconomic characteristics are based on zip code averages from the 2011–2015 ACS data.

Specifically, the damages disproportionately impact communities of color, zip codes with little to no shale development, and zip codes with lower levels of employment. Furthermore, zip codes that were exposed to more than half of all flared natural gas extracted less than 20% of the resource wealth during the sample time period. This indicates that the welfare gains from shale development are not equitably distributed across the population. These results reinforce the importance of environmental justice and distributional considerations in climate and environmental policy discussions. However, our analysis does not capture the full scope of benefits and costs from shale development. For example, the impacts on historically disadvantaged communities, such as the Fort Berthold Indian Reservation in North Dakota, are not considered. Nor does our analysis identify the mechanisms driving the pattern of disproportionate exposure of disadvantaged communities to flaring. These caveats emphasize the importance of additional research on the distributional impacts of flaring policies.

Our findings have implications for current debates regarding flaring policy both globally and within the United States. The Permian Basin and Eagle Ford of Texas both have a higher population density and level of flaring than North Dakota. This indicates that current efforts by Texas regulatory authorities to reduce flaring may yield substantial health benefits. At a global level, our results indicate that policies, such as the World Bank's recent flaring initiative, could benefit the health of individuals located in countries with low flaring combustion efficiency or with population centers proximate to flaring activity, such as Nigeria. Our results and back of the envelope analysis suggests that policies that focus solely on the external costs of green house gas emissions and the foregone value of natural gas are missing a substantial component of the cost of flaring natural gas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jpubeco.2022.104601.

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