$PM_{2.5}$ Pollution from Oil and Gas Activity in the Permian Basin: An Economic Analysis of its Human Health Impacts and Damages[1]

Andrew L. Goodkind, Ph.D.

Benjamin A. Jones, Ph.D.

Casey L. Leek, MS

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Department of Economics, University of New Mexico, Albuquerque, NM 87131

[1] The opinions expressed here are solely those of the authors. All errors are our own. Andrew L. Goodkind (agoodkind@unm.edu) is an Assistant Professor, Department of Economics, University of New Mexico; Benjamin A. Jones (bajones@unm.edu) is an Associate Professor, Department of Economics, University of New Mexico; and Casey L. Leek (caseyleek1@unm.edu) is a Ph.D. student and research assistant, Department of Economics, University of New Mexico. The authors would like to acknowledge the funding provided by the State of New Mexico that supported this research.

Executive Summary

Particulate matter that is less than 2.5 micrometers in diameter, known as $PM_{2.5}$, is among the most damaging air pollutants to human health. The peer-reviewed literature shows that exposure to $PM_{2.5}$ can lead to cardiovascular and respiratory diseases and premature mortality. Ongoing oil and gas (O&G) activity in the Permian Basin region of New Mexico and Texas is a known source of $PM_{2.5}$ pollution through emissions of precursor pollutants. Against this backdrop, there are clear challenges and opportunities for addressing the public health impacts and associated economic damages of $PM_{2.5}$ from the Permian Basin O&G sector, including opportunities to better understand the scale and scope of the $PM_{2.5}$ problem in this region.

In this white paper, we undertake a four-phase study of $PM_{2.5}$ pollution from O&G activity in the Permian Basin. Phase 1 undertakes a location-specific analysis of O&G emissions of $PM_{2.5}$ precursors (VOC, NO_X, SO_2, and primary $PM_{2.5}$), including an investigation of emissions trends over time. Phase 2 investigates spatial and temporal trends in total ambient $PM_{2.5}$ pollution concentrations in the Permian Basin region to provide context for how the O&G sector has affected pollution levels in the area. Phase 3 uses an attribution analysis to connect O&G precursor emissions to $PM_{2.5}$ concentrations, allowing us to identify the contribution of the O&G sector to $PM_{2.5}$ in the Permian Basin and in regions beyond. Finally, Phase 4 estimates the human health impacts and associated dollar-denominated damages of $PM_{2.5}$ attributable to Permian Basin O&G emissions.

Three key findings emerge:

1. Emissions from O&G activity contribute, on average, **27.5%** of $PM_{2.5}$ concentrations in the Permian Basin, over 2011-2017. We find that VOC emissions from O&G activity are the largest source of $PM_{2.5}$ precursor emissions, primarily from oil well tanks.
2. In 2017, the most recent year of data available, we estimate that, nationwide, **638 premature deaths** were associated with $PM_{2.5}$ from the Permian Basin O&G sector. The majority of these deaths occurred outside of the Permian Basin, indicating that O&G activity is impacting human health in both *local* and *distant* communities.
3. Nationwide, the total premature mortality damages of Permian Basin O&G-sourced $PM_{2.5}$ were **$6.57 billion** (in 2022 inflation-adjusted dollars) in 2017. We estimate that for each **$1 in revenue** generated from the sale of oil and gas in the Permian Basin in 2017, **$0.11** in damages were created nationwide from premature mortality associated with $PM_{2.5}$ from O&G activity in the basin.

Given concerns about the $PM_{2.5}$ pollution impacts of O&G activity in the Permian Basin, this work provides a rigorous assessment of the magnitude and scale of the problem, for the first time. Considerations of the human health impacts and economic damages of $PM_{2.5}$, including the sources and types of emissions of primary concern, are important factors that should influence how the Permian Basin states of New Mexico and Texas approach regulations and policies aimed at mitigating the harms from O&G activity. We offer this white paper as evidence-based admissible information for ongoing air pollution policy discussions in the Permian Basin.

1. Introduction

Particulate matter with a diameter of less than 2.5 micrometers, known as $PM_{2.5}$, is a significant contributor to air pollution problems in the Permian Basin, and beyond. Covering over 81,000 square miles in southeast New Mexico (NM) and west Texas (TX), the Permian Basin is a major oil and gas producing region in the United States (US) (The County Information Program, Texas Association of Counties, 2020; US Census Bureau, 2021). For context, as of September 2022, the Permian Basin produced the majority (~66%) of all crude oil drilled for in the US, making it the single largest oil producing area in the country (US EIA, 2022a).

The Permian Basin includes 55 counties in NM and TX (Figure 1) and these counties have a combined 2020 population of approximately 1.39 million people. The area shown in gray in Figure 1 constitutes the primary study region for this white paper, covering the extent of the basin and several small and mid-sized cities, such as Lubbock and Midland (in TX) and Roswell and Carlsbad (in NM).

As both a direct and indirect by-product of oil and gas (O&G) activity in the Permian Basin, $PM_{2.5}$ is created. Sources of ground-level $PM_{2.5}$ in the Permian include windblown mineral dust and soils from extractive activities, fossil fuel combustion from vehicles, machinery, and other equipment, gas flaring, as well as secondary emissions from atmospheric chemical reactions of pollutant precursors such as nitrous oxides (NO_X), sulfur dioxide (SO_2), and volatile organic compounds (VOC). Exposure to $PM_{2.5}$ is associated with asthma exacerbation, decreased lung function, nonfatal heart attacks, respiratory diseases, and premature mortality (US EPA, 2022a). With recent and substantial growth in O&G activity in the Permian Basin since 2012, there are questions about its impacts on $PM_{2.5}$ pollution in New Mexico, Texas, and beyond, including impacts to human health and associated economic damages of $PM_{2.5}$ exposure.

The objective of this analysis is to estimate the health impacts and associated monetary damages from $PM_{2.5}$ pollution in the Permian Basin over 2011-2017 using various data sources from the US Environmental Protection Agency (US EPA) and the expert literature in this area. The analysis includes four components. First, we identify $PM_{2.5}$ precursor emission trends from O&G activity in the Permian Basin using choropleth maps, including an investigation of sources and locations. Second, we investigate spatial and temporal trends in total $PM_{2.5}$ concentrations in the region, from all sources, including O&G. Third, we perform an attribution analysis and calculate ground-level $PM_{2.5}$ concentrations due to Permian Basin O&G activity for the entire US. As will be shown in the analysis, prevailing wind and weather patterns indicate that multiple US states, outside of NM and TX, are impacted by $PM_{2.5}$ emissions from the Permian Basin. Fourth, we use concentration-response functions and attribution data on $PM_{2.5}$ concentrations to estimate the human health impacts and economic damages (focusing on premature mortality) associated with Permian Basin generated $PM_{2.5}$ pollution.

Figure 1: Permian Basin counties and major cities in New Mexico and Texas.

Following this approach, several key findings emerge:

1. Emissions from the Permian Basin O&G sector account for **27.5%** of $PM_{2.5}$ concentrations in the basin, on average, over 2011-2017. We find that VOC emissions are the primary driver of this $PM_{2.5}$, with the single largest O&G source of VOC being leaks from oil well tanks.
2. Even including the impact of the O&G sector, total $PM_{2.5}$ concentrations in the Permian Basin are below both US national and southwest US regional averages. This is likely due to low background sources of $PM_{2.5}$, unrelated to O&G activity. These results suggest that the Permian Basin is not a $PM_{2.5}$ pollution spatial outlier and is therefore not currently a significant area of concern with regards to compliance with the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ set by the US EPA.
3. In 2017, we estimate that, nationwide, **638 premature deaths** were associated with $PM_{2.5}$ from the Permian Basin O&G sector. Out of the nationwide total, 212 deaths (33%) occurred in the Permian Basin while 426 deaths (67%) occurred outside of the basin, in other parts of Texas and New Mexico, but also in neighboring states and beyond. These

results suggest that Permian Basin O&G activity is having significant human health impacts on both *local* and *distant* communities.

4. Nearly **50%** of total nationwide premature deaths due to Permian Basin O&G-sourced $PM_{2.5}$ occurred in Texas, in 2017. By contrast, New Mexico's share was only **5.6%**. Thus, despite being a major producer of oil and gas, New Mexico experiences a relatively small share of the human health burden from $PM_{2.5}$ associated with Permian Basin O&G activity. Most impacts occur in Texas.
5. Nationwide, total premature mortality damages of Permian Basin O&G-sourced $PM_{2.5}$ were **$6.57 billion (2022$)** in 2017. Damages in the Permian Basin proper were $2.16 billion (2022$), equivalent to 33% of the nationwide total. Texas experienced $3.25 billion (2022$) in associated premature mortality damages in 2017 (nearly 50% of nationwide total damages), while damages in New Mexico totaled $371 million (2022$) (5.6% of nationwide damages).
6. Finally, we estimate that for each **$1 in revenue** generated from the sale of oil and gas in the Permian Basin in 2017, **$0.11 in damages** were created nationwide from premature mortality associated with $PM_{2.5}$ from O&G activity in the basin.

1.1 Background on $PM_{2.5}$ and $PM_{2.5}$ pollution in the Permian Basin

Particulate matter (PM) can be naturally occurring or created through human activity and industrial processes. Naturally occurring sources include dust and dirt (US EPA, 2016a). Other sources of PM are wildfires, car emissions, and industrial plants (US EPA, 2016a). $PM_{2.5}$ is a specific type of PM that has a diameter of less than 2.5 micrometers. For comparison, $PM_{2.5}$ is 36 times smaller in diameter than an average grain of sand, which is why it is often referred to as "fine" particulate matter (US EPA, 2016a).

$PM_{2.5}$ can either be directly emitted from sources (known as primary $PM_{2.5}$) or can be formed in the atmosphere through chemical reactions of gases and organic compounds (known as secondary $PM_{2.5}$) from $PM_{2.5}$ precursor pollutants including nitrous oxides (NO_X), sulfur dioxide (SO_2), volatile organic compounds (VOC), and ammonia (NH_3) (California Air Resources Board, n.d.; US EPA, 2019). NO_X is produced by industrial sources such as power plants and vehicles (US EPA, n.d.). SO_2 is created through burning fossil fuels at power plants and using high sulfur fuel in vehicles (US EPA, 2016b). VOCs come from a variety of household products and building materials, and also occur naturally from plants and vegetation (US EPA, 2014b). NH_3 mostly comes from agricultural production processes (New York State Department of Health, 2005). The actual composition of $PM_{2.5}$ is heterogeneous and varies by region and the sources of the pollution (Frank, 2012). Rather than regulating $PM_{2.5}$ based on its composition, air quality regulations focus on the diameter of the particulates when setting and enforcing standards (California Air Resources Board, n.d.).

The US Environmental Protection Agency (US EPA) under guidance from the 1970 Clean Air Act enforces the National Ambient Air Quality Standards (NAAQS). The NAAQS covers six pollutants, including annual-average concentrations of $PM_{2.5}$ (US EPA, 2014a) which is intended to provide protection (on a health impact basis) to those who are most at risk to air pollution (e.g., the elderly and children). The $PM_{2.5}$ standard, since 2012, is limited to 12.0 micrograms per cubic meter ($\mu g/m^3$) annually, measured as a consecutive three-year average (US EPA, 2014a). It is important to note there is no consensus on what is considered a "safe" level of exposure and even low levels of $PM_{2.5}$ can have adverse health impacts (Papadogeorgou et al., 2019). Recognizing this, the US EPA has announced a proposed decision (as of January 2023) to strengthen the $PM_{2.5}$ standard from 12 $\mu g/m^3$ to within the range of 9.0 to 10.0 $\mu g/m^3$ (US EPA, 2023).

$PM_{2.5}$ is of particular interest because the smaller or finer the particulate, the longer it can stay suspended in the air and the deeper it can travel in the respiratory system (Cao et al., 2013). Dockery et al. (1993) determined $PM_{2.5}$ to be especially hazardous by showing increased mortality rates in areas with high concentrations of fine particulates, which contributed to the US EPA incorporating $PM_{2.5}$ into the NAAQS in 1997 (Cao et al., 2013). In addition to its negative health effects, $PM_{2.5}$ can travel significant distances from its source leading to downwind health impacts.

The US EPA determines the areas of the country that are in attainment and those that are not in attainment with the NAAQS $PM_{2.5}$ standard. As of May 2022, only nine US counties or areas are currently in nonattainment with the $PM_{2.5}$ standard, according to the US EPA, and none of the areas are in the Permian Basin (US EPA, 2021). However, rising O&G activity in the Permian Basin has raised concerns regarding future challenges for $PM_{2.5}$ pollution in this area, especially if the $PM_{2.5}$ standard is strengthened, as currently proposed by the US EPA in 2023.

In New Mexico, $PM_{2.5}$ is not regulated outside of US EPA NAAQS standards, but it is indirectly legislated through the precursors NO_X and VOC as part of the 1978 Ozone Attainment Initiative (NMED, n.d.). Under New Mexico state statute 74-2-5.3 NMSA 1978, NMED is tasked with intervening to reduce ozone pollution when ozone levels surpass 95% of the NAAQS standard in a given attainment area (NMED, n.d.). In 2022, NMED modified their rulemaking over ozone pollution in the state by directly regulating ozone precursors NO_X and VOC in the O&G sector; termed the Ozone Precursor Rule (Oil and Gas Sector Ozone Precursor Pollutants, 2022). In the NM Permian Basin, Chaves, Lea, and Eddy counties are included in the 2022 Ozone Precursor Rule, allowing the state to set standards for NO_X and VOC in these areas. As ozone precursors (NO_X and VOC) overlap with $PM_{2.5}$ precursors, the Ozone Precursor Rule will potentially impact $PM_{2.5}$ concentrations in the NM Permian Basin in addition to affecting ozone levels. However, given the recency of this rule, we cannot estimate its $PM_{2.5}$ impacts in this work due to data limitations.

$PM_{2.5}$ concentrations are officially monitored using air quality monitoring stations that are owned and operated by state environmental agencies. The New Mexico Environment Department (NMED) currently has ten air quality monitors in southern NM. Of these, only the Carlsbad and Hobbs monitors are located within the NM section of the Permian Basin and only the Hobbs station actively monitors $PM_{2.5}$. This means that the entire NM Permian Basin area, covering roughly 17,000 square miles, has $PM_{2.5}$ officially monitored by only a single station (US Census Bureau, 2021).

In Texas, air quality monitoring stations are maintained by the Texas Commission on Environmental Quality (TCEQ). There are eight monitoring stations located within the Texas section of the Permian Basin (TCEQ, 2023).[2] Of the eight TX Permian Basin monitoring stations, only two collect data on $PM_{2.5}$ concentrations (Lubbock County and Odessa Gonzales) (TCEQ, 2023). Geographically, this covers the north and central areas of the basin, respectively.

[2] Air quality monitoring stations in the TX Permian Basin (with nearest city in parentheses): Lubbock County (Lubbock), Big Spring Midway (Midland), Midland Avalon Drive (Midland), Goldsmith Street (Odessa), Odessa Westmark Street (Odessa), Odessa-Hays Elementary School (Odessa), Odessa Gonzales (Odessa), Abilene Industrial Boulevard (Abilene).

This means that the entire TX Permian Basin has $PM_{2.5}$ only officially measured by two stations (Railroad Commission of Texas, n.d.).

Outside of $PM_{2.5}$, ozone and methane levels also present air quality challenges for the Permian Basin, leading the US EPA to recently focus their attention on the area. In August 2022, the US EPA began helicopter surveillance of the Permian Basin using infrared cameras (US EPA, 2022b). The goal is to better identify sources of methane and VOC emissions from O&G activity. Methane is a greenhouse gas that contributes to the formation of ozone and climate change (UN Environment Programme, 2021). VOCs also contribute to the formation of ozone, in addition to contributing to $PM_{2.5}$ as a precursor pollutant.

1.2 Oil and Gas Production Information in the Permian Basin

The Permian Basin is the largest producing region of crude oil in the US (US EIA, 2023). Horizontal drilling and horizontal fracking (unconventional drilling) have driven oil production in the region higher, by over four times as much, since 2010 (NM Energy, Minerals and Natural Resources Department, 2023; The Railroad Commission of Texas, n.d.). Natural gas production is four times greater in Texas and seven times greater in New Mexico than in 2010 (NM Energy, Minerals and Natural Resources Department, 2023; The Railroad Commission of Texas, n.d.). Key to the production growth are the technological improvements in drilling. The average horizontal well is now over 10,000 feet while in 2010 the distance was 3,879 feet (US EIA, 2022b). As a consequence of technological improvements, unconventional drilling wells surpassed traditional well numbers in 2014 and as of 2016 represented nearly 70% of all wells in the United States (US EIA, 2018). As of September 2022, New Mexico supplied 16% of US crude oil while Texas had 50% of the country's daily crude oil production (US EIA, 2022a). Data from 2021 shows 6% of the country's daily natural gas output is produced in New Mexico and 27% comes from Texas (US EIA, 2021).

In 2021, New Mexico produced 447 million barrels of oil (BBL) and over 1.7 billion MCF (1,000 cubic feet) of natural gas (NM Energy, Minerals, and Natural Resources Department, 2022). In contrast, in 2010 New Mexico only produced 63.2 million BBL of oil and 432 million MCF of natural gas (NM Energy, Minerals, and Natural Resources Department, 2022). In Texas, between 2010 and 2021, oil production increased from 271 million BBL to 1.1 billion BBL. Natural gas over the same time period increased from 1.16 billion MCF to 4.99 billion MCF (The Railroad Commission of Texas, n.d.).

Figure 2 shows total oil and natural gas production in the Permian Basin, by state and year, between 2006-2022. With the expansion of unconventional drilling, production was able to increase exponentially from roughly 2010-onwards, peaking in 2021. Total revenue from sales of natural gas (based on annual average Henry Hub spot prices) and crude oil (based on annual average Cushing, OK WTI spot prices) produced in the Permian Basin is also shown in the bottom panel of the figure. Texas oil sales generate most revenue in the basin, though sales of oil and gas from New Mexico have recently risen.

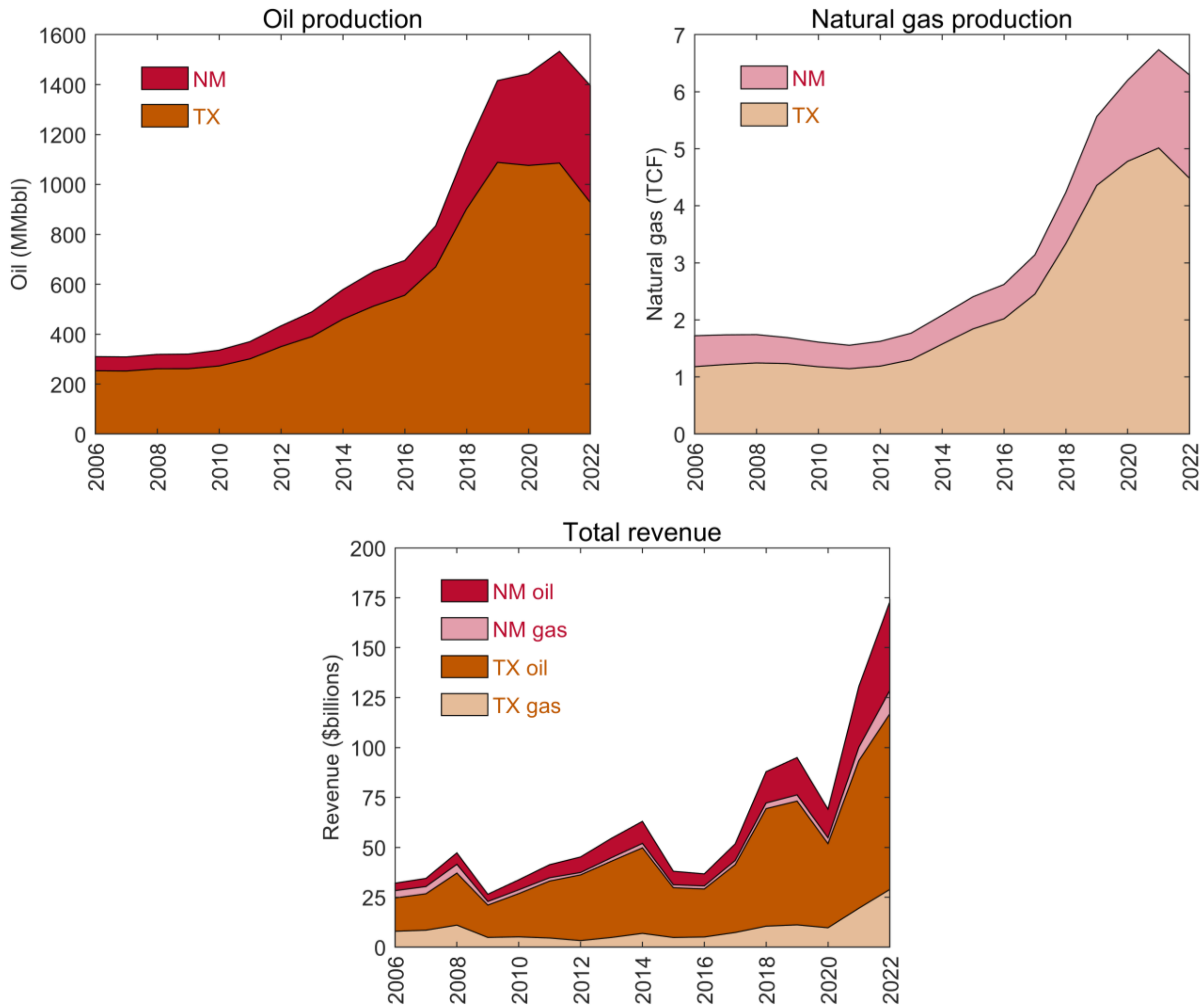

Figure 2: Permian Basin oil (million barrels of oil; MMbbl) and natural gas (trillion cubic feet; TCF) production and total revenue (billions of USD), by state and year (2006-2022). Sources: NM Oil Conservation Division, the Railroad Commission of Texas, and authors' calculations.

Increased oil and natural gas production can impact the local environment through multiple pathways including $PM_{2.5}$, methane emissions, VOC, and ozone concentrations. The activities contributing to emissions are similar across drilling types and include drilling activity, vehicle transportation emissions, venting, flaring, and holding ponds (Moatari-Kazerouni, 2019). A key impact difference between conventional and unconventional drilling, suggested by Moatari-Kazerouni (2019), is that unconventional drilling is more demanding on resources due to longer drilling times and more effort being needed in the process.

While not the focus of this analysis, issues surrounding methane emissions in the Permian Basin are also another air pollution concern. Robertson et al. (2020) estimated that methane emissions in the Permian Basin are 5.5 to 9 times higher than the US EPA estimates for the region (which estimate 1.5% of produced natural gas is leaked) (Chen et al., 2022). Chen et al. (2022) found 9.4% of produced natural gas is lost in the production process when they measured leaks using aircraft surveillance of the NM Permian Basin.

In 2021, New Mexico took steps to limit methane flaring to 2% of production, implying a 98% capture rate by December 2026 (State of New Mexico, 2021). While not related to the $PM_{2.5}$ analysis undertaken in this paper, future work and attention on methane pollution in the Permian Basin is likely warranted.

1.3 Economic Impacts of Permian Basin Oil and Gas Activity

Growth in Permian Basin O&G activity has had significant economic impacts on both New Mexico and Texas.

In NM, the O&G industry contributed $5.3 billion to state revenue in fiscal year 2021, of which $2.96 billion went to the NM state budget (NM Oil & Gas Association, 2021). A key contribution is the funding going towards education. In 2021, $152 million in NM state education funding came from taxes and revenues associated with the O&G industry in the NM Permian Basin. In 2020, employees in the "Mining, Quarrying, and Oil and Gas Extraction" industry had average wages of $81,452 while the average for the NM Permian Basin counties across all other professions was $53,362 (*Economic, Labor, and Employment Overview Lea, Chaves and Eddy Counties*, 2021). In terms of employment, some 13,501 people were employed in 2021 in the mining, quarrying, and oil and gas extraction field in the NM Permian Basin (*Economic, Labor, and Employment Overview Lea, Chaves and Eddy Counties*, 2021). According to the New Mexico Oil and Gas Association, the O&G industry supports 41,187 jobs across the NM Permian counties with the majority of those jobs in Lea and Eddy counties (NM Oil & Gas Association, 2021).

Similarly, Texas has experienced economic benefits of O&G activity. The TX Permian Basin added 87,603 jobs from 2009-2019 and in Midland County over 20,000 jobs were added over the same period (TIPRO, 2020). The Perryman Group (2020) estimates that $82.5 billion in wages, $5.9 billion in local tax revenue, and an additional $7.9 billion in state taxes originate in the TX Permian Basin, annually. Their estimates show that Permian Basin O&G activity supports approximately 10% of the entire Texas economy, equating to $163.8 billion in gross product.

The population of the Permian Basin has also been impacted by O&G development. Between the 2010 and 2020 US Census, NM Permian Basin counties experienced substantial population growth. Eddy and Lea counties had the highest population growth of all NM counties of 15.8% and 15.0%, respectively (Research and Polling Inc., 2021). By comparison, NM on average experienced 2.8% population growth over 2010-2020 (Research and Polling Inc., 2021). The TX Permian Basin on average had an 8.6% population increase from 2010-2020 (Office of the Texas Comptroller, 2022*)*. The most growth occurred in Andrews (25.9%) and Midland (24.2%) counties, both of which are in the TX Permian Basin region.

1.4 Environmental and Human Health Impacts of Permian Basin Oil and Gas Activity

Oil and gas activity present several environmental challenges, including for air pollution, which can impact human health outcomes. To provide a spatial framework for our analysis, Adgate et al. (2014) categorized health impacts from unconventional natural gas production across the US at four different spatial levels: global, regional, local, and well site. While global concerns are important, the focus of our analysis is on the regional and local impacts from $PM_{2.5}$ air pollution. Adgate et al. (2014) also analyzed sources of pollutants and the processes from hydraulic fracking that produce chemical, physical, or safety hazards. For $PM_{2.5}$, potential emissions sources are listed as dust and drill cuttings from well pad construction and drilling, and leaks from oil well tanks. $PM_{2.5}$, and the precursor NO_X, are included in diesel emissions from trucks, heavy equipment, generators, and gas flaring. Our focus is on such sources.

$PM_{2.5}$ is especially hazardous to human health as its small size means that it can cross through the lungs into the circulatory system (Feng et al., 2016). Feng et al. (2016) examined how $PM_{2.5}$ can have negative health consequences even at levels less than the current NAAQS standard for $PM_{2.5}$. Their review of the literature concluded that increased $PM_{2.5}$ not only impacts the respiratory system but also increases the risk of cardiovascular problems, diabetes, and negative birth outcomes. Some of the potential mechanisms identified by Feng et al. (2016) include metabolic activation (changes in cell structure), inflammation of tissue, and oxidative stress (cell damage). The mechanisms that cause cell damage can lead to pulmonary and cardiovascular problems, childhood asthma, and diabetes (Feng et al., 2016). In line with the findings in Feng et al. (2016), Fann et al. (2018) point out, “there is no population-level concentration threshold for fine particles” so even at low $PM_{2.5}$ concentrations, impacts to human health exist and can be damaging.

Premature mortality is also affected by $PM_{2.5}$. Yang et al. (2023) in a meta-analysis of 51 studies on air pollution found positive correlations between mortality and $PM_{2.5}$ concentrations. Similarly, Zanobetti and Schwartz (2009) focused on 112 US cities from 1999-2005 and determined that a 10 $\mu g/m^3$ increase in 2-day average $PM_{2.5}$ led to a 0.98% increase in mortality and a 1.68% increase in respiratory deaths.

Fann et al. (2018) present an analysis quantifying the health impacts of $PM_{2.5}$ and ozone from projected O&G activity across the US in the year 2025. Their estimates show that the Permian Basin will have some of the highest $PM_{2.5}$ and ozone concentrations attributable to O&G in the country by 2025. Texas is estimated to have 130 cases of premature mortality in 2025 due to $PM_{2.5}$ from O&G activity and 130 cases from ozone. Combined, Fann et al. (2018) estimate that O&G activity in TX will contribute 1.4 premature deaths per 100,000 people in TX in 2025 due to $PM_{2.5}$ and ozone.

Other estimates of the costs and benefits of O&G activity in the Permian Basin also exist. Loomis and Haefele (2017) estimate environmental damages from hydraulic fracking across 14 states (including NM and TX). The estimated damages per ton for VOC, SO_2, primary $PM_{2.5}$ and NO_X are $431, $3,701, $10,559, and $587, respectively (Loomis & Haefele, 2017). Total damages are between $1.0 billion and $15.3 billion from primary $PM_{2.5}$, between $9 billion and $20.8 billion from NO_X, between $2.1 billion and $3 billion from VOC, and between $477 million and $2.9 billion from SO_2.

In addition to its impacts on $PM_{2.5}$ pollution, there are other environmental impacts connected to O&G activity. While not the focus of this analysis, we briefly highlight two salient ones for the Permian Basin: water pollution and seismic activity. Water pollution occurs when water and chemicals used in the fracking process contaminate groundwater sources. The fracking process involves injecting water and chemicals into wells to create pressure to force gasses out of the ground (National Geographic Society, 2022). Through this process some chemicals can leak into the surrounding medium. Hill and Ma (2017) showed a 2.7% increase in water pollution (including, but not limited to methane, ethane, propane, oil, saline, and other hydraulic fracking chemicals used in the production process; see McIntosh et al., 2019) if a well pad was within 0.5 km of a sampling site.

Seismic activity, or earthquakes, are also another environmental concern. The increase in underground pressure caused by hydraulic fracking has been shown to cause earthquakes in areas surrounding injection locations, putting local communities at an increased risk for seismic activity (Weingarten et al., 2015). There are also economic impacts of earthquakes associated with O&G activity. Mothorpe and Wyman (2021) found housing prices are negatively impacted by increases in seismic activity due to hydraulic fracking in Oklahoma.

1.5. Conceptual Framework

Before proceeding, we provide a conceptual framework for the analysis undertaken in this work (Figure 3) and outline the rest of the white paper.

Our primary objective is to characterize $PM_{2.5}$ pollution created from O&G emissions in the Permian Basin and to connect that pollution to human health impacts and associated economic damages. To do so, we begin (in Section 2) with an analysis of Permian Basin O&G emissions of $PM_{2.5}$ precursor pollutants VOC, SO_2, NO_X, and primary $PM_{2.5}$. These precursors, with the exception of primary $PM_{2.5}$, combine in the atmosphere to form secondary $PM_{2.5}$. We collect data from the US EPA on observed O&G emissions for this part of the analysis.

Next, we move from emissions to studying $PM_{2.5}$ directly by showing trends and estimates of ambient $PM_{2.5}$ concentrations in the Permian Basin, including $PM_{2.5}$ from both O&G and non-O&G sources (in Section 3). Spatial satellite data on $PM_{2.5}$ are used for this part of the analysis.

Then, an attribution analysis is undertaken (in Section 4) to link precursor pollutant emissions from the O&G sector to induced changes in $PM_{2.5}$ concentrations. The attribution analysis provides modeled results showing the direct effect of Permian Basin O&G emissions on $PM_{2.5}$ levels through the combination of primary and secondary $PM_{2.5}$.

From there, we use concentration-response functions from the epidemiology and public health literatures to estimate the human health impacts (focusing on increased instances of adult premature mortality) of $PM_{2.5}$ generated by Permian Basin O&G activity (in Section 5).

Finally (in Section 6), we apply commonly-used health economic damage metrics (value of a statistical life or VSL) from the US EPA to value the estimated changes in premature mortality associated with O&G emissions in the Permian Basin. This provides us with an estimate of the economic damages from $PM_{2.5}$ exposure tied to O&G emissions.

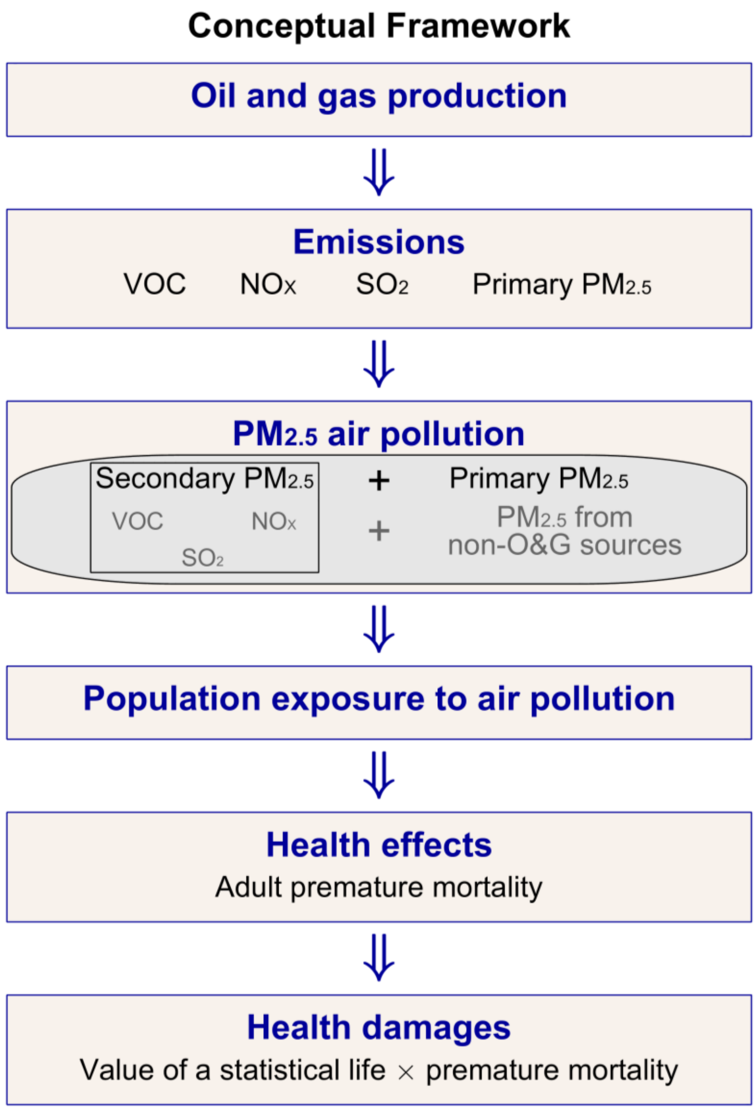

Figure 3: Conceptual framework for studying $PM_{2.5}$ pollution from Permian Basin oil and gas activity and its associated human health impacts and economic damages.

2. Emissions of $PM_{2.5}$ Precursors from O&G in the Permian Basin

In this section, we begin our analysis with an investigation of the emissions of $PM_{2.5}$ precursors (NO_X, VOC, SO_2) and primary $PM_{2.5}$ specifically sourced from oil and gas activity in the Permian Basin. Emissions of these precursors, with the exception of primary $PM_{2.5}$, combine to form secondary $PM_{2.5}$ in the atmosphere through chemical reactions. The total $PM_{2.5}$ concentration, which will be used to evaluate health impacts in Section 5, combines primary and secondary $PM_{2.5}$. In what follows, time trend figures and source-location maps are presented to show the dynamic impacts of O&G activity on precursor emissions and the geographic sources of those emissions, by pollutant type.

Data on emissions of primary $PM_{2.5}$ and $PM_{2.5}$ precursors (NO_X, SO_2, and VOC) were collected from the National Emissions Inventory (NEI), a database compiled by the US EPA every three years (US EPA, 2022c). We used the three most recently available versions of the NEI: 2011, 2014, and 2017. The NEI provides annual estimates of emissions by various types of sources and location. We obtained emissions of sources directly associated with O&G production from the counties identified as within the Permian Basin.

We collected emissions from two broad categories: point sources and nonpoint sources. Point sources are generally larger emitters and are required to monitor and report their emissions to the US EPA. These sources have precise geographic locations associated with their emissions. Each point source is categorized by its North American Industry Classification System (NAICS) code, and we collected those sources with NAICS codes relating to O&G production.[3] Quantities of emissions of the four precursor pollutants, the emission stack height, and the geographic coordinates of each point source were collected for each O&G point source in the Permian Basin counties.

Nonpoint sources are defined by the NEI as including emissions for sources which individually are too small in magnitude to report as point sources (US EPA, 2022c), and their emissions are estimated at the county level and by their Source Classification Code (SCC). We obtained emissions for those sources with an SCC sector classified as “Industrial Processes – Oil & Gas Production”.[4] Quantities of each of the four precursor pollutants at the county level were collected for each O&G SCC in the Permian Basin.

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[3] Included NAICS codes: 2111 (Oil and Gas Extraction), 21112 (Crude Petroleum Extraction), 21113 (Natural Gas Extraction), 211111 (Crude Petroleum and Natural Gas Extraction), 211112 (Natural Gas Liquid Extraction), 213112 (Support Activities for Oil and Gas Operations), 221210 (Natural Gas Distribution), 237120 (Oil and Gas Pipeline and Related Structures Construction), 486110 (Pipeline Transportation of Crude Oil), 48621 (Pipeline Transportation of Natural Gas), 48691 (Pipeline Transportation of Refined Petroleum Products), and 48699 (All Other Pipeline Transportation).

[4] This includes all 10-digit SCCs starting with 2310.

Figure 4 shows Permian Basin O&G emissions of $PM_{2.5}$ precursors, by pollutant type and source (point or nonpoint), over the years 2011, 2014, 2017. Note that 2017 is the most recent year of NEI data available at the time of the analysis. Nonpoint source VOC emissions are by far the single largest source of $PM_{2.5}$ from O&G activity, averaging ~500 metric tons per year, across the three years.

In the Permian Basin, in particular, we observe that the top four nonpoint source VOC emissions for O&G are: (i) oil well tanks (51.4% of total VOC O&G nonpoint emissions); (ii) condensate tanks (10.4% of total); (iii) truck and rail loading of crude oil (8.2% of total), and; (iv) emissions off of produced water from oil wells (4.8% of total). A key conclusion from Figure 4 is that nonpoint source VOC emissions from O&G activity, primarily from oil well tanks, are the dominant contributor to $PM_{2.5}$ precursor emissions in the Permian Basin.

O&G-related emissions of NO_X and SO_2 are moderate in magnitude, by comparison to VOC, and emissions of primary $PM_{2.5}$ (which constitute direct emissions of solids and liquids) are minimal in Figure 4. However, similar to VOC emissions, NO_X and SO_2 emissions are predominately from nonpoint sources, including compressor engines and artificial lift engines (NO_X) and natural gas wellheads and oil well tanks (SO_2). There are also several significant point source emissions of NO_X and SO_2, including 4-cycle lean engines and combustion engine turbines (NO_X) and oil and gas flaring and sulfur recovery units (SO_2).

There is a slight upward trend in precursor emissions from 2011 to 2017, most notably for NO_X and SO_2. Note that this upward trend is occurring simultaneously with increased O&G production in the Permian Basin over the 2011-2017 time period (from Figure 2).

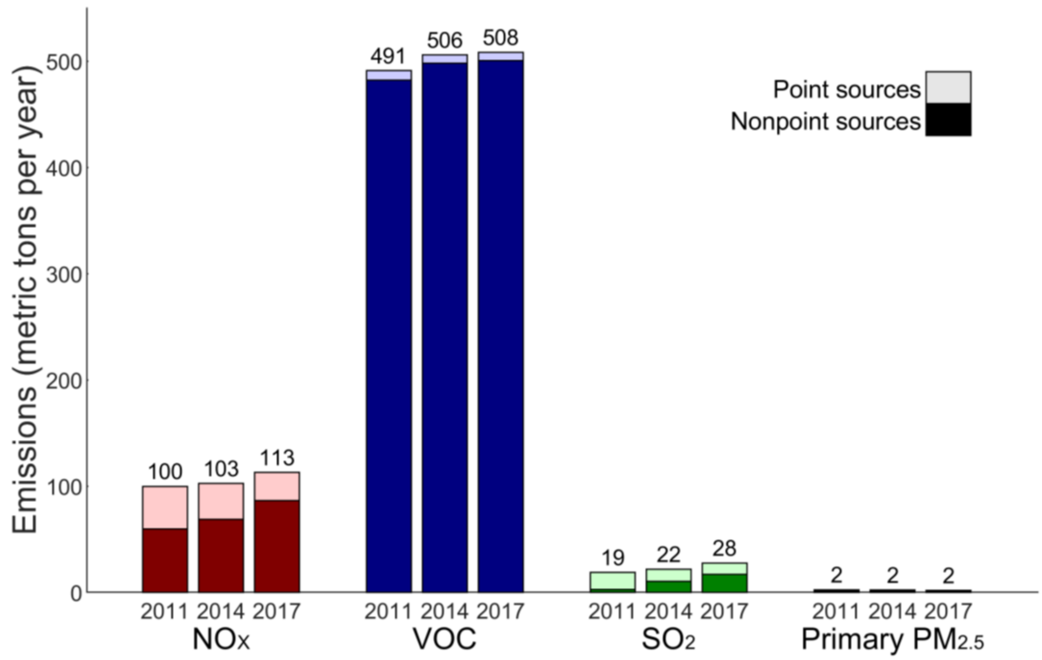

Figure 4: Precursor emission trends (metric tons) by year, precursor pollutant type, and source (point or nonpoint) from the Permian Basin O&G sector. Point sources (nonpoint sources) are denoted by lighter (darker) shading. Sources: NEI and authors' calculations.

To understand the geographic sources of the Permian Basin precursor emissions shown in Figure 4, we present, in Figure 5, a source-location map of 2017 point source precursor emissions, by pollutant type. 2017 is focused on since it is the most recent NEI data year available.

From Figure 5, most point source precursor emissions from the O&G sector are from SO_2 and NO_X with only small amounts of VOC and primary $PM_{2.5}$. Emissions of SO_2 and NO_X are largest along the New Mexico and Texas border, though NO_X sources are also observed in the southern and eastern areas of the Texas Permian Basin. VOC and primary $PM_{2.5}$ emission point sources are more uniformly distributed throughout the basin. Several point source locations for SO_2 have emissions rates of $\geq$1000 metric tons in 2017, which is substantial. The single largest SO_2 point source in the NEI data are emissions from natural gas flaring (49.7% of total SO_2 O&G point source emissions).

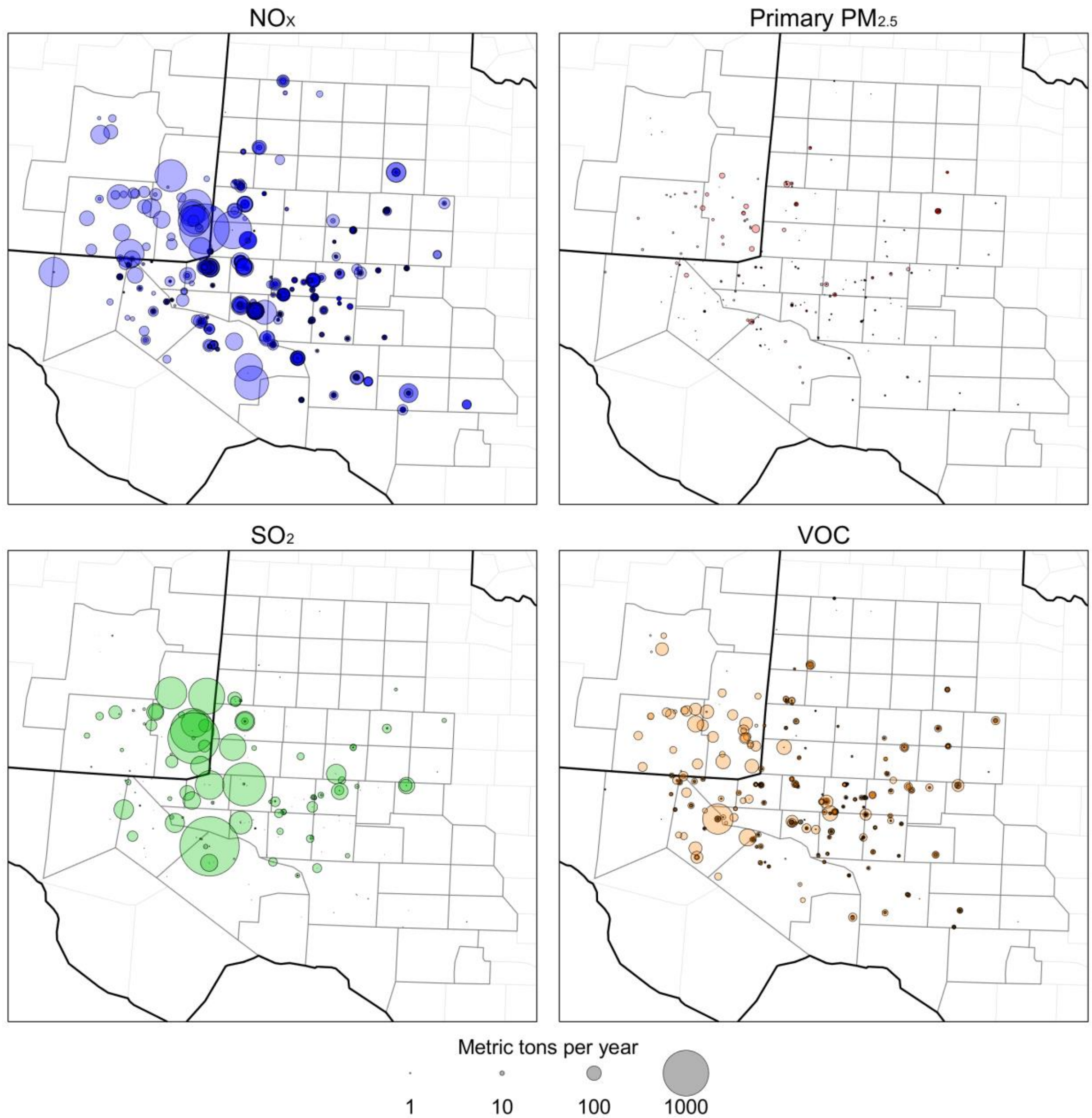

Figure 5: Point source emission locations (metric tons) in 2017 from Permian Basin O&G activity, by precursor pollutant type. Darker colors represent overlapping sources of emissions. Larger circles represent greater masses of emissions (see legend). Sources: NEI and authors' calculations.

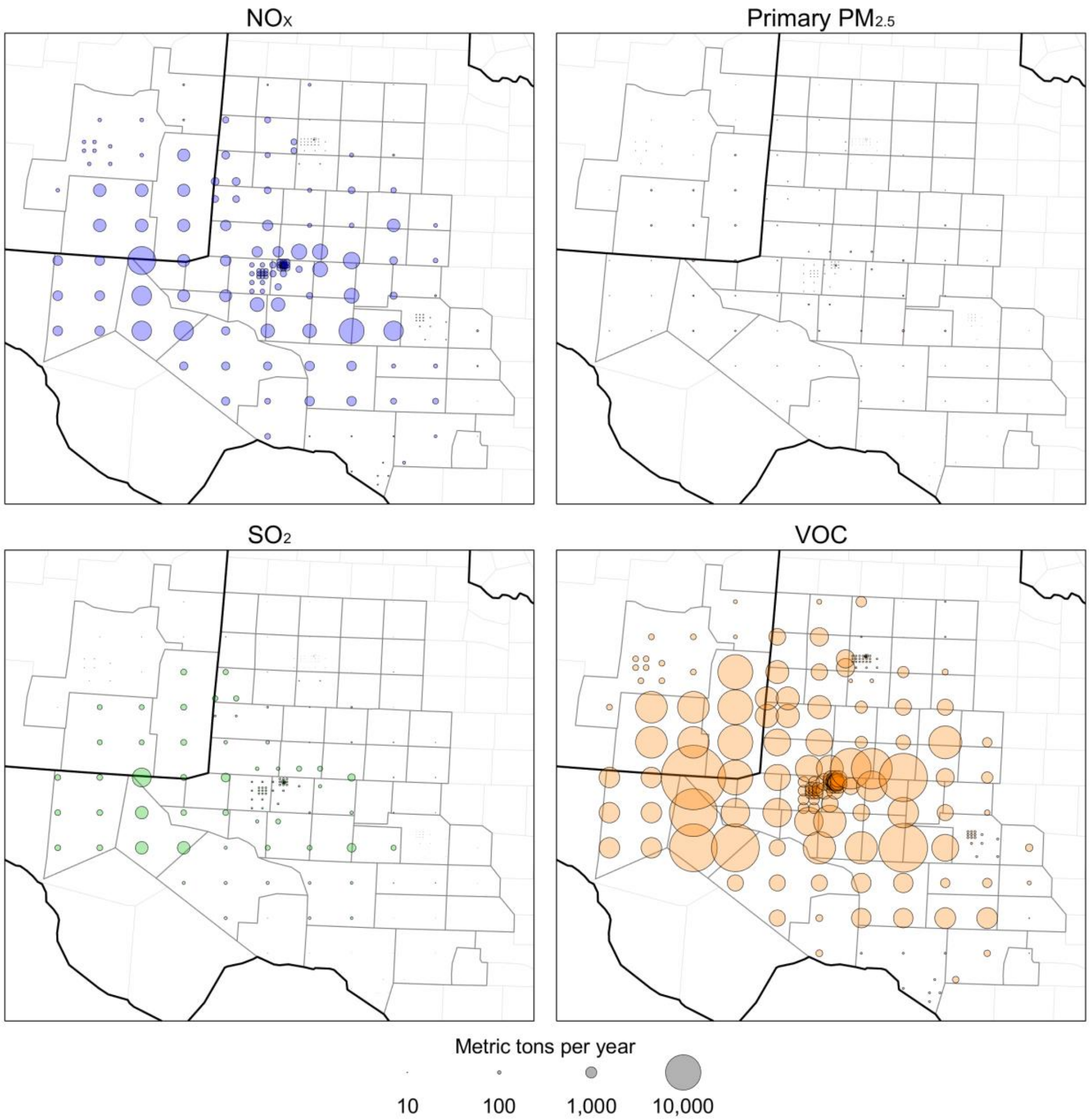

Figure 6: Nonpoint source emission locations (metric tons) in 2017 from Permian Basin O&G activity, by precursor pollutant type. Darker colors represent overlapping sources of emissions. Larger circles represent greater masses of emissions (see legend). Sources: NEI and authors' calculations.

In Figure 6, we produce a similar source-location map to the one Figure 5, but now isolate nonpoint sources of 2017 O&G emissions in the Permian Basin. Note the change in the magnitude of the legend in Figure 6; the highest category is now 10,000 metric tons of emissions. Also note that the NEI only provides nonpoint source locations at the county level (compared to precise geographic coordinate locations for the point source data previously shown). The county-level data was apportioned to grid cells—for use in the air-quality modeling in Section 4—uniformly to each grid cell within each county. This leads to the grid-like structure of sources observed in Figure 6.

By far, the dominant nonpoint source of pollution from the O&G sector is VOC (Figure 6). This contrasts with the point source emissions results (Figure 5) where VOC emissions were substantially lower compared to the other precursor pollutant types, with the exception of primary $PM_{2.5}$. Several Permian Basin counties are responsible for 10,000 metric tons (or more) of nonpoint source VOC in 2017 directly associated with O&G activity. Additionally, the high levels of nonpoint source VOC emissions are observed throughout the basin, in both New Mexico and Texas.

According to the 2017 NEI data, 83% of the mass of all nonpoint source emissions due to O&G activity are from VOC, with most of these emissions coming from oil well tanks. Emissions of NO_X are the second largest nonpoint source and are also fairly evenly distributed throughout the basin, but at magnitudes substantially lower than VOC. The majority (59.6%) of nonpoint source NO_X in the NEI is from two types of combustion engines (4-cycle rich burn compressors and artificial lift engines). Negligible amounts of nonpoint source SO_2 and primary $PM_{2.5}$ emissions are observed from O&G in 2017.

There are three key takeaways from Figures 5 and 6: (i) the largest O&G source of $PM_{2.5}$ precursor emissions in the Permian Basin is nonpoint source VOC; (ii) oil well tanks are the single largest emissions source in the Permian Basin (constituting 36.4% of the total mass of $PM_{2.5}$ precursor emissions in 2017), and; (iii) point source emissions of NO_X and SO_2, primarily from natural gas flaring and combustion engines (2-cycle and 4-cycle lean burn), are also significant sources of $PM_{2.5}$ precursors in the basin.

3. General $PM_{2.5}$ Trends in the Permian Basin

In this section, we present results showing general trends in $PM_{2.5}$ in the Permian Basin. Note that this analysis includes *aggregate* $PM_{2.5}$ concentrations from all sources; not exclusively from O&G. This will provide some background and context on ambient pollution levels in the region, which will be useful as we transition in later sections into a detailed investigation of $PM_{2.5}$ that is specifically sourced from O&G activity.

Annual $PM_{2.5}$ concentration data were obtained from van Donkelaar et al. (2021) for the years 2010-2020. These data are derived from satellite measurements of $PM_{2.5}$ concentrations that are then calibrated based on ground-based observations. The data are presented in high-resolution grid cells (0.01˚×0.01˚) across North America. These data provide complete coverage of the Permian Basin, giving the best representation of the long-term and spatial trends in $PM_{2.5}$ concentrations over this period. Alternatively, monitoring station data of $PM_{2.5}$ concentrations are available for a very limited number of locations across the Permian Basin and thus cannot illustrate the spatial gradients in concentrations. The US EPA uses the monitoring station data for regulatory purposes to assess NAAQS compliance, which is not the focus of our analysis. For our purposes of understanding the trends in $PM_{2.5}$ concentrations across the Permian Basin, the satellite data is the best available option.

We collected the satellite data and then averaged it across uniform 5×5 km grid cells in the Permian Basin for each year. Figure 7 shows these annual averages of ambient $PM_{2.5}$ concentrations for the years 2010-2020. Over this period, levels of $PM_{2.5}$ averaged 6.16 micrograms per cubic meter ($\mu g/m^3$) across the basin. For context, the US national average of $PM_{2.5}$ over 2010-2020 was 8.54 $\mu g/m^3$, according to US EPA air trends data. For the southwest US, in particular, the $PM_{2.5}$ average over this period was 7.15 $\mu g/m^3$, per the US EPA. Thus, average $PM_{2.5}$ concentrations in the Permian Basin were between 2.38 $\mu g/m^3$ and 0.99 $\mu g/m^3$ lower than the US national and southwest regional averages, respectively, over 2010-2020. This suggests that this region of heavy O&G activity is not an outlier with regards to either national or regional pollution trends over the same period of time.

After peaking in 2011, Permian Basin $PM_{2.5}$ levels have generally been declining through the year 2020 (Figure 7). The highest $PM_{2.5}$ levels are observed along the US-Mexico border in Texas, but mostly within Mexico. Seeing as there are no major cities or sources of industrial or agricultural activity on this section of the border, would suggest the presence of natural causes to explain the large $PM_{2.5}$ concentrations observed in this area (e.g., geography, topography, local weather, etc.). Interestingly, the US-Mexico border "hotspot" largely disappears by 2020 (when O&G production in the Permian Basin was near its peak; see Figure 2), becoming no more significant in terms of $PM_{2.5}$ levels than the surrounding region. For these reasons, we conclude that O&G activity is unlikely to be the primary cause of this localized hotspot.

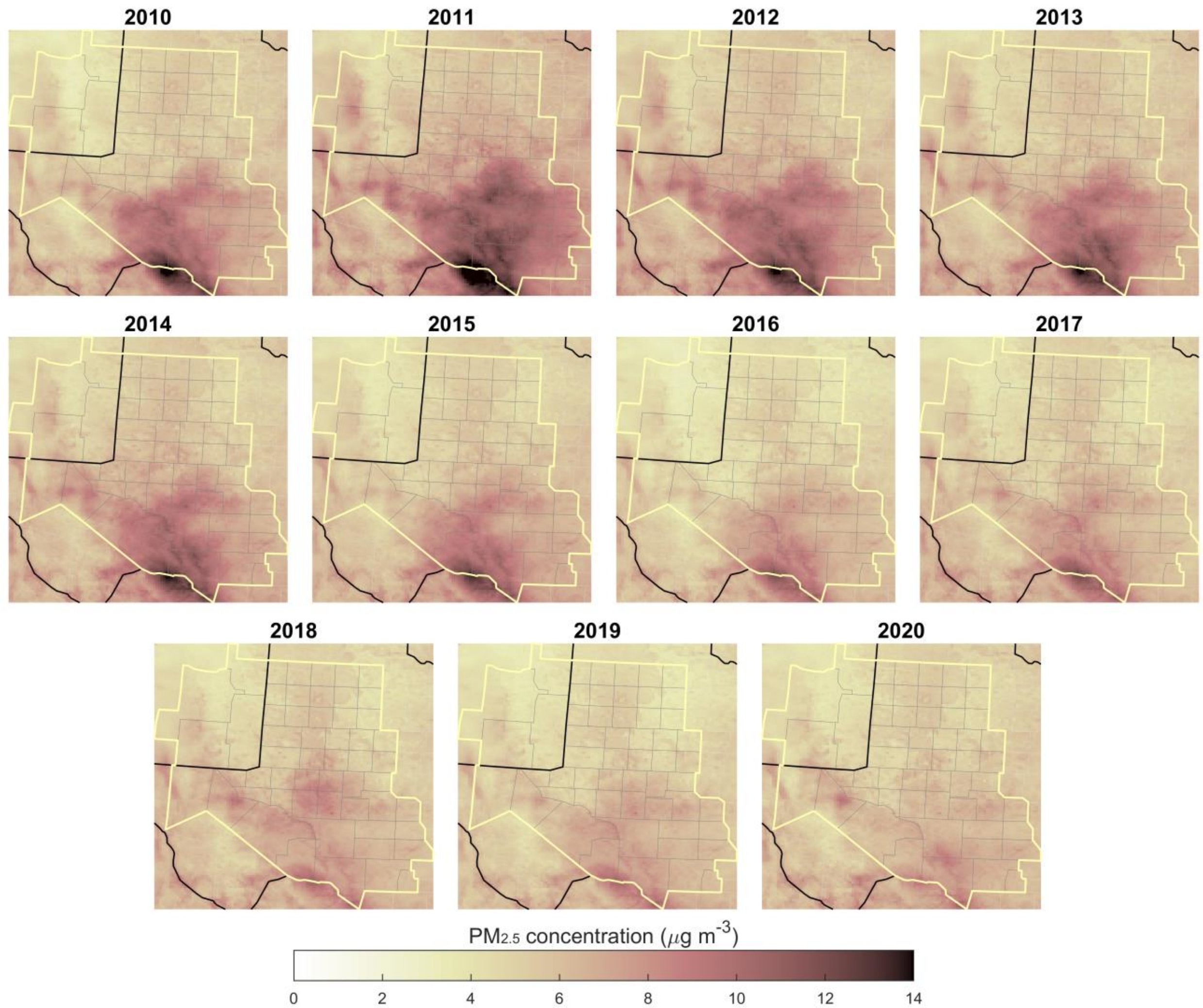

Figure 7: Average ambient $PM_{2.5}$ concentrations (μg/m^3) in the Permian Basin, by year (2010-2020). 5×5 km gridded data shown. Outer boundary of Permian Basin counties in yellow. Sources: van Donkelaar et al. (2021) and authors' calculations.

Other notable hotspots of $PM_{2.5}$ are observed throughout the western and central portions of the Texas section of the Permian Basin, including around the cities of Midland, Odessa, and Pecos. In New Mexico, one noticeable hotspot is the north-to-south area in Chaves County, which largely corresponds to highway US 285 (a major transportation artery in the region) and the cities located on the highway, including Roswell and Carlsbad.

Comparing the O&G precursor emission source-location maps (Figures 5 and 6) with the $PM_{2.5}$ concentration map (Figure 7), shows some overlap between precursor emissions (especially for nonpoint source VOC) and $PM_{2.5}$ concentrations in the central portions of the Texas Permian Basin, particularly around Midland and Odessa. This is suggestive evidence that O&G activity is contributing to the observed $PM_{2.5}$ hotspot in this area. However, stronger evidence is needed and will be provided in the next section through the use of attribution modeling.

To present the Figure 7 results in a different manner, we show in Figure 8 the annual trends in $PM_{2.5}$ concentrations, averaged over all grid cells in the Permian Basin counties between 2010-2020. For completeness, the interquartile and 95% ranges of the data are also shown.

Consistent with Figure 7, we observe largely declining ambient $PM_{2.5}$ levels in the Permian Basin over time, with the average peaking at slightly over 7 $\mu g/m^3$ in 2011 and the average lowest at ~5.5 $\mu g/m^3$ in 2016. However, from 2016-2020, the mean trendline is largely flat, indicative of no significant changes in $PM_{2.5}$ levels over this period. This is despite an exponential growth in O&G production in the Permian Basin from 2016-2020 (from Figure 2). Taken together, the evidence is suggestive that average ambient $PM_{2.5}$ levels and O&G production are not strongly associated in the Permian Basin; as O&G production increased from 2016-2020, annual average $PM_{2.5}$ concentrations across all basin counties were largely unchanged. To be clear, this is not meant to imply that O&G and $PM_{2.5}$ are unrelated (because a relationship indeed exists as will be shown in detail in the next section). Rather, these results suggest that the impact of increased O&G activity from 2016-2020 on ambient $PM_{2.5}$ levels is small in magnitude; significant increases in ambient $PM_{2.5}$ are not observed across the Permian Basin counties despite large increases in O&G production. However, it may be the case that in the absence of the realized increases in O&G production, $PM_{2.5}$ levels would have continued on their 2011-2016 downward trend; we simply do not know what might have happened in such a counterfactual world.

An explanation for why the exponential growth in O&G production over 2016-2020 did not lead to substantial increases in average ambient $PM_{2.5}$ levels in the Permian Basin should be studied and investigated in future work. A myriad of possible explanations may exist, including: changes in other non-O&G precursor emissions over the same time period; technological advancements and improvements in the mechanical, technical, or operational processes used to extract, transport, and refine O&G; changes in weather and wind patterns; or changes in upwind sources of $PM_{2.5}$ (outside of the Permian Basin).

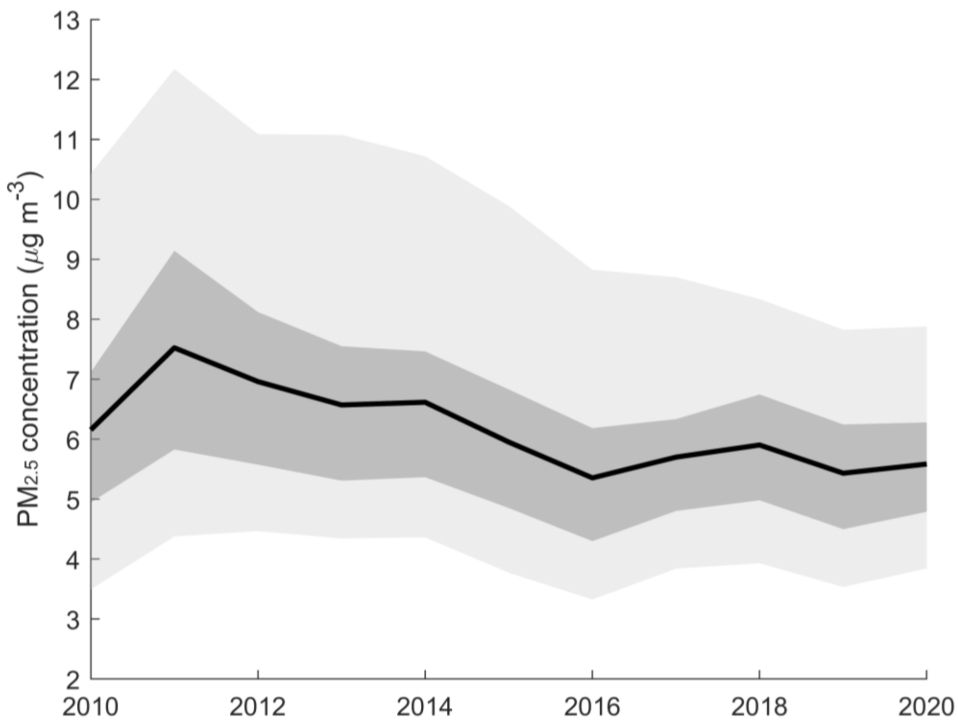

Figure 8: $PM_{2.5}$ trends in the Permian Basin for the years 2010-2020. The black line is mean $PM_{2.5}$ concentration ($\mu g/m^3$), the dark gray band is the interquartile range (25th to 75th percentile), and the light gray band is the 95% range of the data (2.5th to 97.5th percentile). Sources: van Donkelaar et al. (2021) and authors' calculations.

Lastly, we calculated the share of Permian Basin counties that are out of compliance with the US EPA NAAQS standard for $PM_{2.5}$, which is currently set at 12.0 $\mu g/m^3$ annually, measured as a consecutive three-year average. Using our data, which we note is different from the official data used by the US EPA for ascertaining NAAQS compliance (for reasons previously explained), we find that there are no Permian Basin counties above the $PM_{2.5}$ standard over the 2010-2020 period. This suggests that O&G activity, in addition to other economic sectors in this region and upwind sources, are not resulting in $PM_{2.5}$ levels that are leading to NAAQS nonattainment concerns under the current US EPA standard. In fact, ambient $PM_{2.5}$ concentrations in the Permian Basin are generally well below the current standard and are well below both national and regional averages.

4. Attribution Analysis of O&G Precursor Emissions on $PM_{2.5}$ Concentrations

In this section, we show the specific impacts of Permian Basin O&G emissions on $PM_{2.5}$ concentrations by performing an attribution analysis on the precursor emissions previously presented in Section 2. An attribution analysis enables us to isolate the direct effect of O&G emissions on $PM_{2.5}$ concentrations in New Mexico, Texas, and, because of dispersion, in neighboring states.

The attribution analysis combines the emissions of the four precursor emissions (primary $PM_{2.5}$, NO_X, SO_2 and VOC) from the years 2011, 2014 and 2017, with an air quality model that estimates the change in $PM_{2.5}$ concentrations at all downwind locations attributable to these emissions. The air quality model is the InMAP Source-Receptor Matrix (ISRM) (Goodkind et al., 2019) which isolates for any emission source the change in $PM_{2.5}$ concentrations at all downwind locations. The ISRM is a model consisting of grid cells across the US. For any emission source grid cell i, the model shows for a one-ton change in precursor emissions at the source, the change in $PM_{2.5}$ concentrations in all other grid cells in the model. These relationships between emission sources and downwind receptor grid cell concentrations are called source-receptor coefficients and are identified as π_{ij}^{s}, which represents the change in the $PM_{2.5}$ concentration at receptor grid cell j from a one-ton change in emissions of precursor pollutant s at source i.

The ISRM has variable-sized grid cells, with larger grid cells (48×48 km) in sparsely populated areas, and progressively smaller grid cells (24×24 km, 12×12 km, 4×4 km, 2×2 km, and 1×1 km) for more densely populated areas. To use the ISRM we needed to apportion our emissions to each grid cell in the Permian Basin. For point sources this is straightforward as we use the geographic coordinates of the source and apply the emissions to the grid cell the source is within. For nonpoint sources, which are provided at the county level by the NEI, the process is slightly more involved. We identify all the grid cells whose centroids are within the boundaries of each county, and then apportion the county total of emissions equally among all the identified grid cells.

For our analysis, we sum up the total emissions, e_i^s, of each pollutant s within a grid cell (from both point and nonpoint O&G sources) and multiply by the source-receptor coefficients to calculate the change in $PM_{2.5}$ concentration at each receptor grid cell j, ΔC_j^s, attributable to the O&G emissions:

$$\Delta C_j^s = \sum_{i=1}^{n} e_i^s \cdot \pi_{ij}^s.$$

The total change in $PM_{2.5}$ concentrations, ΔC_j, at grid cell j is the sum of the change associated with each precursor pollutant:

$$\Delta C_j = \Delta C_j^{\text{pri PM2.5}} + \Delta C_j^{\text{NOx}} + \Delta C_j^{\text{SO2}} + \Delta C_j^{\text{VOC}}.$$

In Figure 9, we present our modeled results of the ΔC_j, showing annual $PM_{2.5}$ concentration changes (for 2011, 2014, and 2017) due to O&G precursor emissions in the Permian Basin.[5] Note that because these results are the product of an attribution analysis, it is correct to interpret them as the direct, isolated impact of O&G precursor emissions.[6] Put differently, Figure 9 shows our best estimates of the direct effect of Permian Basin O&G activity on regional $PM_{2.5}$ levels.

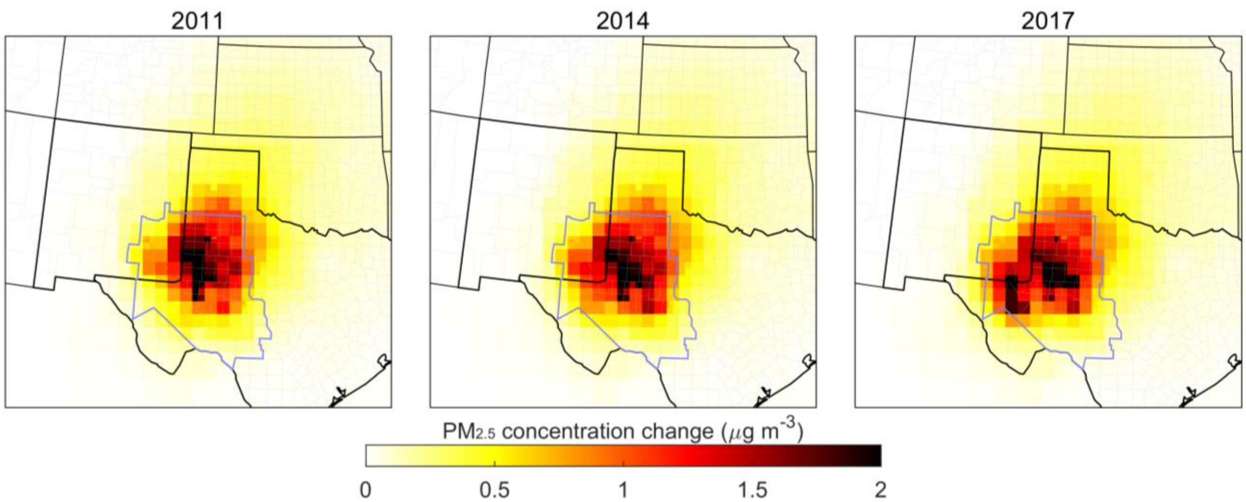

Figure 9: Modeled annual $PM_{2.5}$ concentration changes (μg/m^3) due to Permian Basin oil and gas precursor emissions (of NO_X, SO_2, VOC, and primary $PM_{2.5}$) for years 2011, 2014, and 2017. 1×1 km to 48×48 km gridded data shown (varied based on population density). Permian Basin region outlined in blue. Sources: Goodkind et al. (2019) and authors' modeling results.

The highest magnitude of $PM_{2.5}$ impacts of O&G are localized in and around the Permian Basin counties in west Texas and southeast New Mexico. We estimate that annual $PM_{2.5}$ levels in this region are higher by 1.82 μg/m^3, on average, due to O&G activity. Of this average increase, 1.54 μg/m^3 (or 85%) is due to O&G VOC emissions and 0.16 μg/m^3 (or 9%) is due to O&G NO_X emissions. For context, the background ambient $PM_{2.5}$ concentrations in the Permian Basin in these three years (2011, 2014 and 2017) averaged 6.61 μg/m^3 (from Section 3). These results would therefore suggest that 1.8 μg/m^3 of the ambient average of 6.61 μg/m^3 is directly attributable to O&G activity in the Permian Basin. In the absence of O&G activity, background

[5] Only the years 2011, 2014, and 2017 are shown because the NEI data, which are a required modeling input, are only available in three-year increments.

[6] As with any modeling analysis, uncertainty exists. The attribution analysis here is no exception and the presented modeling results may differ from actual $PM_{2.5}$ concentration changes due to O&G.

ambient $PM_{2.5}$ levels would otherwise be lower by 1.8 μg/m^3, per year, on average. Put differently, we find that the O&G sector, through its emissions of $PM_{2.5}$ precursors, contributes 27.5% of the annual average ambient $PM_{2.5}$ concentrations experienced in the Permian Basin.

As a secondary finding from Figure 9, observe the large spatial dispersion of $PM_{2.5}$. Due to prevailing winds, weather patterns, and atmospheric conditions, the $PM_{2.5}$ created by Permian Basin O&G emissions disperses into non-Permian Basin counties within both New Mexico and Texas, and, beyond into the neighboring states of Oklahoma, Kansas, and Colorado. While the magnitudes of out-of-state impacts are fairly low (<0.5 μg/m^3), we highlight that the air pollution impacts of O&G activity are observed well beyond the Permian Basin, directly impacting distant airsheds and human populations. This suggests that Permian Basin O&G activity is generating a negative externality on people and environments across many states and communities; air pollution impacts are not isolated to the oil and gas producing region alone.

To augment these results, we present, in Figure 10, the year 2017 concentration changes in $PM_{2.5}$ from Permian Basin O&G emissions, but now separated into the specific contribution of each precursor pollutant (i.e., the ΔC_j^s). Figure 10 is a "deconstructed" version of the results shown in Figure 9; summing the grid cell values across all four of the panels in Figure 10 will produce the same result shown in Figure 9 (for 2017). 2017 is focused on here since it is the most recent year of NEI data available.

Figure 10 results suggest that VOC emissions are the predominant O&G source of $PM_{2.5}$. The majority of the changes in $PM_{2.5}$ concentrations shown previously in Figure 9 are thus being driven by VOC emissions. This is consistent with the evidence gathered in Figures 4 and 6, showing substantial and outsized emissions of VOC from the Permian Basin O&G sector. At significantly reduced magnitudes, both NO_X and SO_2 also contribute to O&G-driven increases in regional $PM_{2.5}$ levels. In particular, note the large spatial dispersion of the $PM_{2.5}$ attributable to NO_X emissions, especially when compared to the dispersion of the other precursors. While VOC has a substantial impact on localized $PM_{2.5}$ in the Permian Basin region, its dispersion area into neighboring counties and states is not too dissimilar to that seen for NO_X.

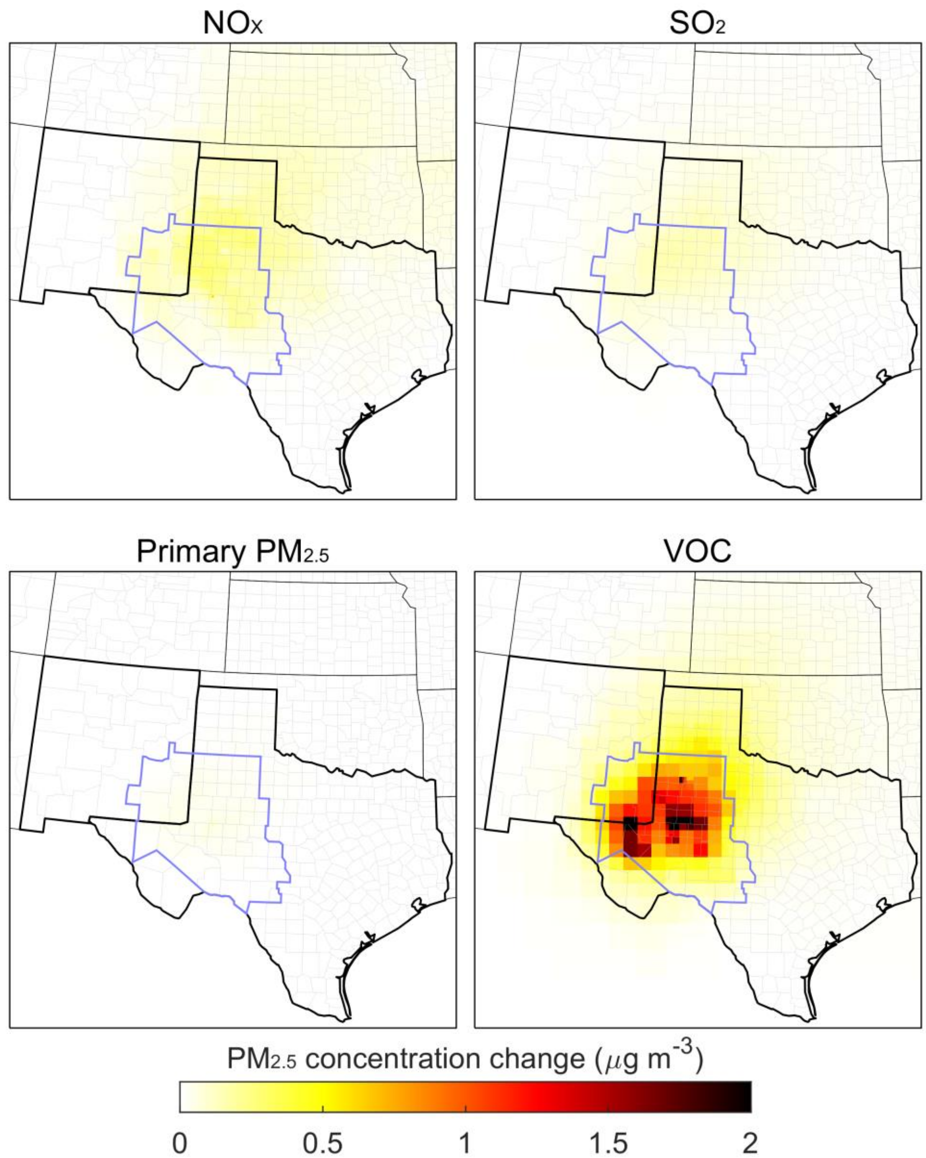

Figure 10: Modeled $PM_{2.5}$ concentration changes ($\mu g/m^3$) in 2017 attributable to Permian Basin oil and gas emissions, by precursor pollutant type. 1×1 km to 48×48 km gridded data shown (varied based on population density). Permian Basin region outlined in blue. Sources: Goodkind et al. (2019) and authors' modeling results.

5. Human Health Impacts of $PM_{2.5}$ Associated With O&G Activity in the Permian Basin

In this section, we present estimates of the human health impacts of $PM_{2.5}$ attributable to Permian Basin O&G activity. Underlying our analysis is the biological phenomena that human exposure to $PM_{2.5}$ pollution is associated with negative impacts to human health. From the peer-reviewed literature, we know that $PM_{2.5}$ exposure is associated with negative impacts to the human respiratory and cardiovascular systems (Xing et al., 2016; Polichetti et al., 2009) and can lead to premature mortality (Apte et al., 2015). In this paper, we focus on $PM_{2.5}$ impacts to premature mortality because these impacts are the most severe and are also the largest source of economic damages associated with air pollution exposure.

By utilizing the results from the $PM_{2.5}$ attribution analysis, shown in the previous section, we can directly estimate the impacts of O&G emissions on premature mortality, through exposure to the $PM_{2.5}$ generated by O&G activity, and through the use of concentration-response functions from the peer-reviewed literature in epidemiology. We perform the analysis for US adults (25+) and, because of dispersion of air pollution, nationwide.

We use a concentration-response function called GEMM (Burnett et al. 2018), that relates changes in $PM_{2.5}$ concentrations to changes in adult premature mortality. The GEMM model is the result of a meta regression that collected data from the literature on the relationship between $PM_{2.5}$ and mortality and used a flexible functional form to produce a nonlinear estimate of the concentration-response function. We use an estimate from GEMM that applies for all adults (age 25+) and for the rate of mortality from all non-communicable diseases plus mortality from lower respiratory infections (NCD+LCI).[7] The concentration-response function is presented as the relative risk of premature mortality (from these causes) compared with the risk at the lowest observed concentration in the GEMM analysis (2.4 $\mu g/m^3$). For instance, for a location with a $PM_{2.5}$ concentration 8 $\mu g/m^3$ *above* the lowest concentration (i.e., a concentration of 10.4 $\mu g/m^3$) it will have a relative risk of 1.093, which means that a person exposed to that concentration is 9.3% more likely to die from one of these causes than someone at the lowest concentration.

The $PM_{2.5}$ concentration changes, attributable to O&G emissions (calculated in Section 4), were at the grid cell level from the ISRM model. For the calculations in this section, we applied the grid-cell level changes to US Census block groups. For each block group centroid, we identified the ISRM grid cell it is within and applied that grid cell's $PM_{2.5}$ concentration change to the block group.

We calculated the premature mortality attributable to the emissions of O&G in the Permian Basin using the relative-risk equations from GEMM (RR_j) and an equation called the population

[7] These diseases constitute approximately 87% of all deaths in the US.

attributable fraction (PAF_j). The PAF shows the share of the total mortality from a cause (or set of causes) that can be attributable to a particular factor:

$$PAF_j = \left(1 - \frac{RR_j\left(C_j^0 - \Delta C_j\right)}{RR_j\left(C_j^0\right)}\right)$$

where C_j^0 is the observed $PM_{2.5}$ concentration in location j (from the satellite derived concentrations in Section 3), and ΔC_j are the changes in $PM_{2.5}$ concentrations attributable to O&G emissions from the Permian Basin (as derived in Section 4).

Then using the PAF, we calculate the total mortality (M_j) attributable to O&G emissions by multiplying the PAF by the total mortality (population times mortality rate) from these causes (NCD+LCI) in a location:

$$M_j = p_j \cdot \lambda_j^0 \cdot PAF_j$$

where the adult (25+) population of a block group is p_j and the baseline mortality rate from NCD+LRI causes is λ_j^0. The mortality rate data comes from the US CDC (Centers for Disease Control and Prevention, 2021) and is the seven-year average of county mortality rates for the NCD+LRI causes. Block group adult populations comes from the 2021 American Community Survey (Manson et al., 2022) and represents the five-year average population from 2017-2021.

Using similar methods, we also calculate the attributable mortality by the type of precursor emissions (M_j^s) using the PAF with the change in concentration due to each pollutant (ΔC_j^s) that was previously shown in Figure 10.

Figure 11 shows the premature mortality impacts of exposure to $PM_{2.5}$ from Permian Basin O&G activity in 2017, by US Census block group. Each block group is represented by a circle whose size indicates the number of instances of $PM_{2.5}$-attributable premature mortality in 2017. The highest magnitude of premature deaths are located in the Permian Basin region of Texas and New Mexico. Due to dispersion of $PM_{2.5}$ across the US, impacts are observed throughout the nation, though generally at very low magnitudes (i.e., <1 death per block group), outside of the basin. All major Texas cities, including Dallas, Austin, Houston, and San Antonio, experienced premature mortality directly attributable to $PM_{2.5}$ generated by Permian Basin O&G activity in 2017. In New Mexico, cities including Albuquerque, Santa Fe, and Las Cruces also faced premature mortality impacts, though generally at reduced magnitudes compared to the impacts observed in Texas.

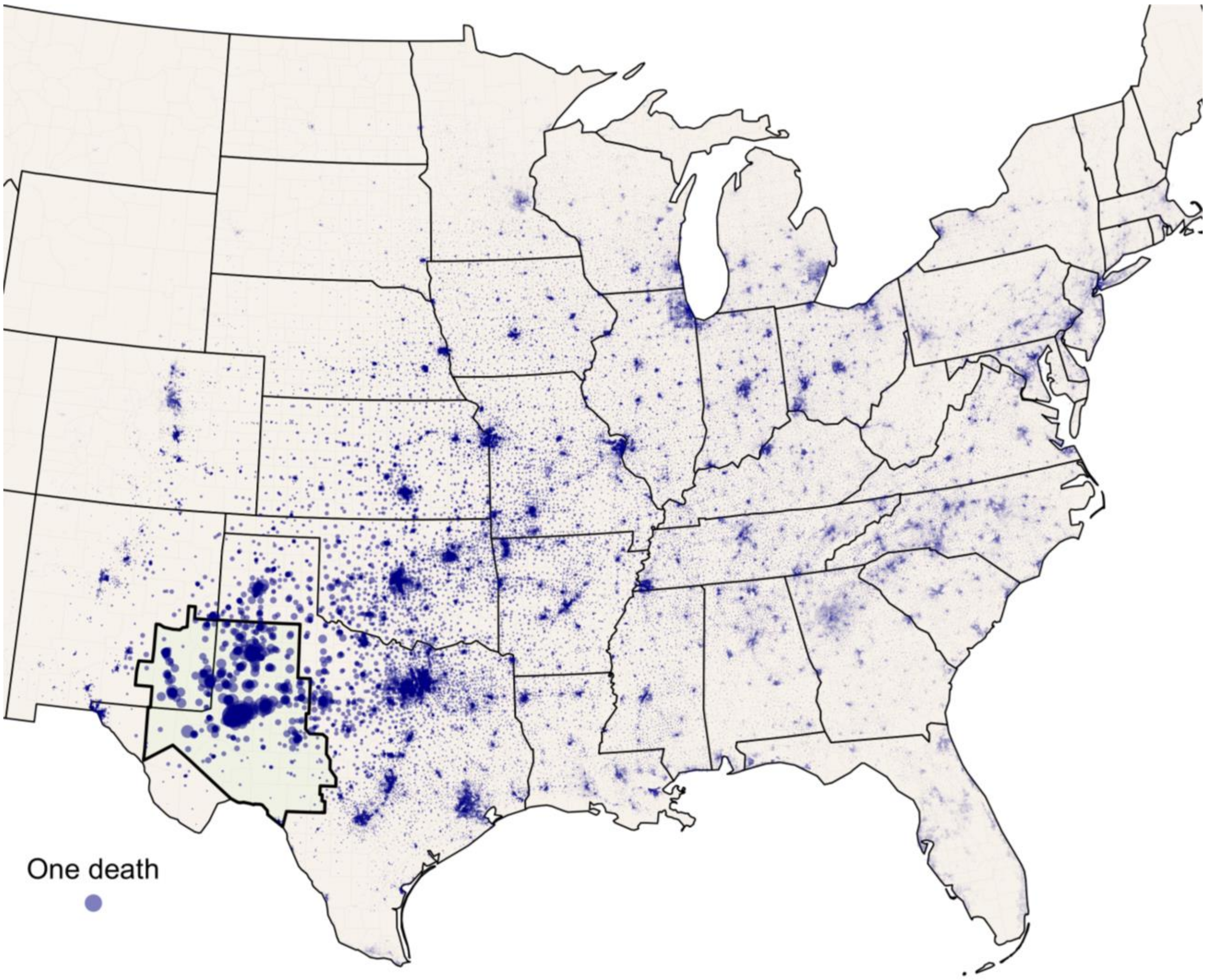

Figure 11: Premature mortality (for adults; 25+) associated with $PM_{2.5}$ exposure from Permian Basin O&G precursor emissions, by US Census block group, for 2017. Circle sizes represent counts of premature mortality cases per block group. Permian Basin counties outlined in black and highlighted. Source: authors' calculations.

In 2017, we estimate that, nationwide, a total of 638 premature deaths were associated with $PM_{2.5}$ from the Permian Basin O&G sector.[8] The majority, 53%, of these deaths were caused by $PM_{2.5}$ created from emissions of VOC. No other single precursor pollutant had such an outsized influence on premature mortality cases. Out of the nationwide total, 212 deaths (33%) occurred in the Permian Basin proper. This suggests that the majority (67%) of premature deaths due to $PM_{2.5}$ from basin O&G emissions occurred *outside* of the Permian Basin, in neighboring states, but also, to lesser degrees, in distant states and communities (e.g., in the Midwest and northeast US). We conclude from this that Permian Basin O&G activity is having significant *internal* and *external* impacts on the health of populations both inside and outside of the basin proper.

[8] This number represents the nationwide sum of all the blue circles in Figure 11.

To augment the results in Figure 11, we produce, in Figure 12, two charts showing instances of premature mortality due to $PM_{2.5}$ from Permian Basin O&G emissions by precursor pollutant type and by state, for 2017. Starting with the panel on the left, most premature deaths (336 of 638 total cases) are due to VOC emissions and most VOC emissions deaths are located in Texas. Premature deaths due to NO_X emissions were also significant in 2017, and many of those deaths were in distant states. Differential dispersion of the $PM_{2.5}$ created by NO_X can likely explain this finding.

Texas experienced a total of 315 premature deaths due to Permian Basin O&G $PM_{2.5}$ in 2017, compared to 36 premature deaths in New Mexico. Note that Oklahoma actually experienced more Permian Basin O&G-related premature deaths in 2017 than New Mexico. Despite being a major O&G producer in the Permian Basin, New Mexico's sparse population and the region's prevailing west-to-east wind patterns (which push much of the $PM_{2.5}$ eastward) mean that the state experienced relatively fewer premature deaths than Texas and Oklahoma.

Moving to the right panel of Figure 12, we observe, consistent with the left panel, that Texas is affected the most, as a percentage of total premature deaths from a pollutant, from Permian Basin $PM_{2.5}$. 65% (VOC) and 60% (primary $PM_{2.5}$) of total premature deaths in 2017 were located in Texas. By contrast, deaths in New Mexico were never more than 10% of the US nationwide total, across all precursor pollutant types. As an example of the external impact of Permian Basin O&G emissions on distant populations, 46% of total NO_X-related deaths are in states other than Texas and New Mexico (the Permian Basin states) and outside of the neighboring or near-neighboring states of Oklahoma, Kansas, and Missouri. This provides further suggestive evidence of the wide geographic impact of Permian Basin O&G activity across the US.

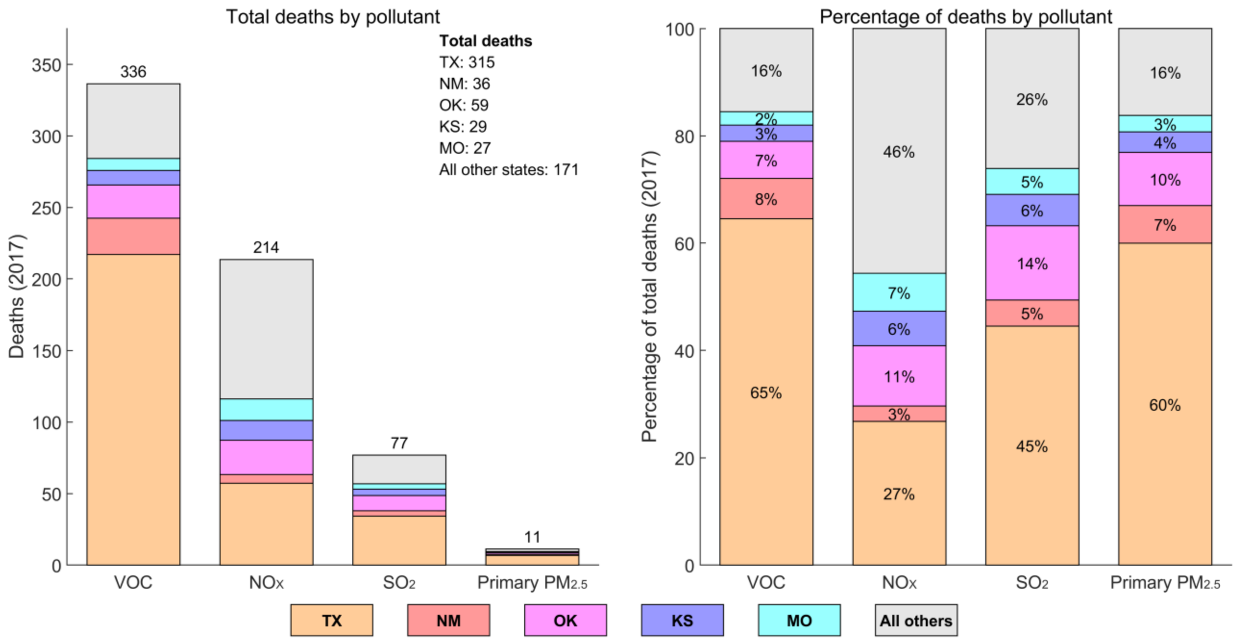

Figure 12: Premature mortality (for adults; 25+) associated with $PM_{2.5}$ exposure from Permian Basin O&G precursor emissions, by precursor pollutant type and state in which the death occurred, for 2017. Total premature deaths (left panel) and percentage of premature deaths by pollutant type (right panel). Source: authors' calculations.

6. Health Economic Damages of $PM_{2.5}$ from Permian Basin O&G Activity

In this section, we estimate the dollar-denominated health economic damages of $PM_{2.5}$ attributable to the Permian Basin O&G sector using the premature mortality estimates from Section 5.

Understanding the monetary damages of air pollution exposure is important for policymaking and regulatory purposes. The US EPA routinely studies the benefits and costs of the Clean Air Act (US EPA, 2022d) in order to provide information on the Act's social impacts to human health, welfare, and natural assets. Decisions surrounding updated policies to adjust the US National Ambient Air Quality Standards (NAAQS) depend, in part, on benefit-cost analyses of human health damages (or avoided damages, as may be the case) of air pollution exposure (US EPA, 2022d).

Such work motivates our investigation of the human health damages of $PM_{2.5}$ from Permian Basin O&G activity. Our results will provide, to the best of our knowledge, the first such economic damage estimates for this region, serving as potentially relevant information on the larger social and welfare impacts of O&G activity in the Permian Basin.

In the results that follow, we show economic damage estimates for premature mortality, using the health incidence estimates from Section 5. Recall that the results in Section 5 showed the number of instances of premature mortality, across the US, due to $PM_{2.5}$ created from O&G emissions in the Permian Basin in 2017. Here, we monetize these estimated premature mortality impacts using the willingness-to-pay (WTP) to avoid exposure health damage metric.

WTP is a monetary value that captures a person's readiness to pay to avoid being exposed to an air pollutant; for $PM_{2.5}$ in this study. Economists often use WTP because it is considered the proper economic measure of value for averting a negative outcome (US EPA, 2022d). WTP values can be elicited from surveys or inferred from observed behavior. For the valuation of premature mortality (our health impact of interest), we employ the value of a statistical life (VSL). VSL is calculated by the summation of individuals' WTP to avoid small increases in mortality risk over a pool of individuals (US EPA, 2022e).

For our purpose, we use the standard VSL adopted by the US EPA, which is equal to $10.3 million (in 2022 inflation-adjusted dollars; 2022$).[9] To estimate the total health damages (for premature mortality) of $PM_{2.5}$ from Permian Basin O&G emissions for 2017, we multiply the VSL by the total number of premature deaths attributable to $PM_{2.5}$ from O&G emissions.

[9] All monetary damage estimates shown in this section are in 2022 inflation-adjusted dollars, which we abbreviate as 2022$. We use the US Bureau of Economic Analysis (BEA) Implicit Price Deflator for the inflation adjustment (US BEA, 2022).

Figure 13 presents the results of these calculations. Shown are the total premature mortality damages of $PM_{2.5}$ from Permian Basin O&G emissions for 2017, by precursor pollutant type (different colors) and by location (shades of the same color). We estimate that nationwide, across the US, total premature mortality damages are $6.57 billion (2022$) due to Permian Basin O&G emissions. Damages in the Permian Basin proper total $2.16 billion (2022$), equivalent to 33% of the nationwide total. This implies that 67%, or $4.41 billion (2022$), of health damages from $PM_{2.5}$ associated with Permian Basin O&G emissions are occurring outside of the basin; in other Texas and New Mexico communities, in neighboring states, and elsewhere across the US.

We further estimate that the health damages in Texas alone, including its section of the Permian Basin region, total $3.25 billion (2022$), and that the damages in New Mexico alone, also including its portion of the Permian Basin, total $371 million (2022$). These results therefore suggest that Texas is experiencing substantially more of the $PM_{2.5}$ health damage burden than New Mexico, which can largely be explained by population differences (Texas has more people than New Mexico, increasing population exposure) and prevailing west-to-east wind patterns that carry $PM_{2.5}$ generally eastward from the Permian Basin (across Texas and neighboring states). Premature mortality damages in Texas constitute 49%, or nearly half, of all nationwide US damages associated with $PM_{2.5}$ from the Permian Basin O&G sector. By contrast, New Mexico's share of total nationwide damages is only 5.6%.

VOC emissions that form $PM_{2.5}$ from O&G activity are the single largest source of premature mortality damages in the Permian Basin and across the US, consistent with earlier sections showing large VOC emissions across the basin. Emissions of NO_X also generate substantial health damages, mostly in states outside of Texas and New Mexico.

We estimate that for each metric ton of Permian Basin O&G precursor emissions in 2017, $19,700 (2022$) in health damages are created from NO_X, $7,400 in damages are created from VOC, $29,200 in damages are created from SO_2, and $65,250 in damages are created from emissions of primary $PM_{2.5}$. Thus, while VOC emissions from O&G lead to the largest number of total attributable deaths, per metric ton of emissions, they are actually the least damaging precursor pollutant. By contrast, primary $PM_{2.5}$ emissions (i.e., direct emissions of $PM_{2.5}$), while there are relatively few of them in the Permian Basin O&G sector (see Figures 5 & 6), are the most health damaging per unit emitted.

By combining data from Figures 2 and 13 (on O&G production and health damages, respectively), we calculate that for each $1 in revenue generated from Permian Basin O&G activity in 2017, $0.11 in damages are created nationwide from premature mortality associated with $PM_{2.5}$ from O&G activity in the basin. This is a key finding of this work. Put differently, $0.11 is our best estimate of the magnitude of the human health externality (for premature mortality from $PM_{2.5}$) created for each $1 in revenue obtained from the sale of oil and gas in the

Permian Basin. The magnitude of this estimate suggests that the health externality created from O&G $PM_{2.5}$ is not trivial.

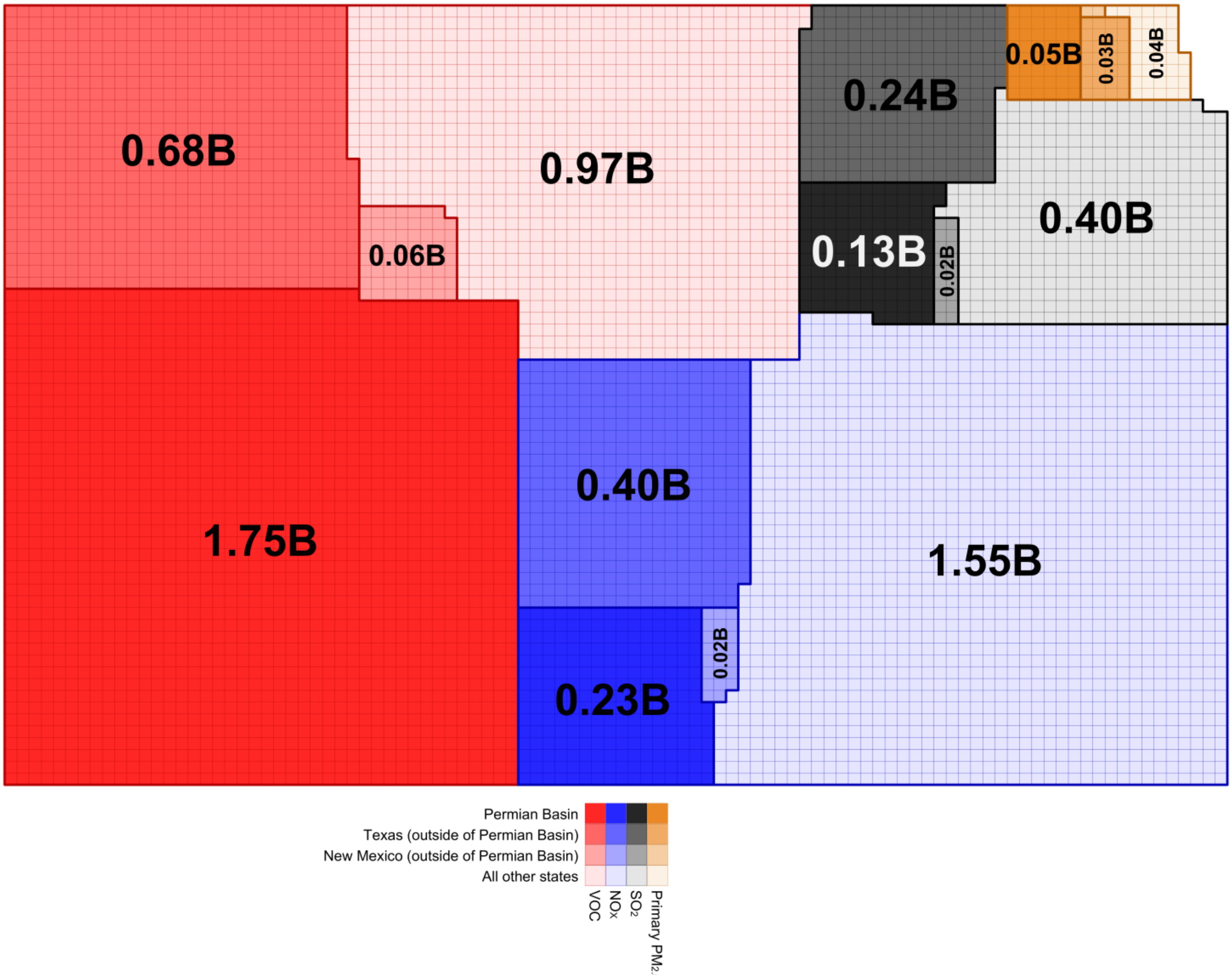

Figure 13: Monetary health damages (for premature mortality; adults 25+) associated with $PM_{2.5}$ exposure from Permian Basin O&G precursor emissions, by precursor pollutant type (different colors) and by location of impact (shades of the same color), for 2017. Each small square box is equivalent to $1 million (2022$) in premature mortality damages. Total damages (in billions of 2022$) listed in black text for each precursor type and location (calculated as the sum of all small boxes for each precursor-location). Source: authors' calculations.

7. Conclusions and Policy Implications

In this paper, we investigated the human health impacts and economic damages of $PM_{2.5}$ pollution attributable to O&G activity in the Permian Basin region of New Mexico and Texas. $PM_{2.5}$ is studied because it is known to be the most damaging air pollutant to human health. Through emissions of precursor pollutants (VOC, NO_X, and SO_2) and through emissions of primary $PM_{2.5}$, we found that the O&G sector is having appreciable impacts on both regional and national $PM_{2.5}$ concentrations. Elevated levels of $PM_{2.5}$ pollution have negative impacts on the health and welfare of residents of Texas and New Mexico, primarily, but also to lesser degrees on people and communities throughout the US due to atmospheric dispersion of pollution.

To the best of our knowledge, this paper is the first rigorous study of $PM_{2.5}$ health impacts and damages due to Permian Basin O&G activity. Studying this topic is important given continued interest and growth of oil and gas production in this region. Empirical estimates of the negative economic externalities associated with O&G production can be a useful input for policymakers who are tasked with weighing the benefits (of which there are many) and costs of the Permian Basin O&G sector when developing evidence-based policy.

We developed a comprehensive data set of Permian Basin O&G sector emissions in New Mexico and Texas over 2011-2017 using NEI data from the US EPA. Using the most recent year of NEI emissions data available (year 2017), we then performed a modeling attribution analysis to connect O&G emissions to $PM_{2.5}$ concentrations. This allowed us to isolate the direct effect of emissions on $PM_{2.5}$ levels. Finally, we estimated the premature mortality impacts and associated economic damages of attributable $PM_{2.5}$ from the Permian Basin O&G sector.

Our key findings are:

- The single largest source of $PM_{2.5}$ in the Permian Basin is from VOC emissions tied to O&G activity. The single largest source of these VOC emissions is oil well tanks.
- Total ambient $PM_{2.5}$ concentrations in the Permian Basin are below both US national and southwest US regional averages. This is likely due to low background sources of $PM_{2.5}$, unrelated to O&G activity.
- In 2017, we estimate that, nationwide, 638 premature deaths were associated with $PM_{2.5}$ from the Permian Basin O&G sector. Out of the nationwide total, 212 deaths (33%) occurred in the Permian Basin while 426 deaths (67%) occurred outside of the basin, in other parts of Texas and New Mexico, but also in neighboring states and beyond.
- Nearly 50% of total nationwide premature deaths due to Permian Basin O&G $PM_{2.5}$ occurred in Texas, in 2017. By contrast, New Mexico’s share was only 5.6%.
- Nationwide, total premature mortality damages of Permian Basin O&G-sourced $PM_{2.5}$ were $6.57 billion (2022$) in 2017. Damages in the Permian Basin proper were $2.16

billion (2022$), equivalent to 33% of the nationwide total. Texas experienced $3.25 billion (2022$) in associated premature mortality damages in 2017 (nearly 50% of nationwide total damages), while damages in New Mexico totaled $371 million (2022$) (5.6% of nationwide damages).
- We estimate that for each $1 in revenue generated from the sale of oil and gas in the Permian Basin in 2017, $0.11 in damages were created nationwide from premature mortality associated with $PM_{2.5}$ from O&G activity in the basin.

The evidence indicates that the state experiencing most of the $PM_{2.5}$-related health impacts and damages of Permian Basin O&G activity is Texas. New Mexico, by contrast, experiences substantially fewer impacts. This is primarily driven by population differences between the two states (which determines the population exposed) and prevailing west-to-east wind patterns that push precursor emissions and $PM_{2.5}$ out of New Mexico towards Texas and other eastern states.

As a policy relevant observation, we find no evidence that the Permian Basin region, in either Texas or New Mexico, has $PM_{2.5}$ levels that are at or near current NAAQS standards set by the US EPA. An implication of this finding is that O&G activity, to the extent that it is having a measurable effect on $PM_{2.5}$ concentrations in the Permian Basin, is not pushing the region out of compliance with current federal air quality standards for $PM_{2.5}$. Over 2010-2020, $PM_{2.5}$ levels in the Permian Basin, from all sources, including O&G, averaged 6.16 $\mu g/m^3$. For reference, the current NAAQS primary standard for $PM_{2.5}$ is set at 12.0 $\mu g/m^3$, annually averaged over three consecutive years. Ongoing discussions by the US EPA to lower the primary $PM_{2.5}$ NAAQS limit to 9-10 $\mu g/m^3$ would still be above our average estimates of Permian Basin $PM_{2.5}$ concentrations. Of course, individual specific locations or counties may differ from the regional averages, and therefore out-of-compliance hotspots are possible within the Permian Basin. Our focus on averages can miss such cases.

Lastly, for regulators and policymakers concerned about $PM_{2.5}$ levels in the Permian Basin (and their associated human health damages), we emphasize that VOC emissions from O&G activity are the single largest source of emissions in the basin. Specifically, VOC emissions from oil well tanks. Policies targeted at controlling, to the extent possible, oil well tank emissions will have potentially large effects on reducing the health impacts and damages associated with the O&G sector.

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