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Assessing Human Health $PM_{2.5}$ and Ozone Impacts from U.S. Oil and Natural Gas Sector Emissions in 2025

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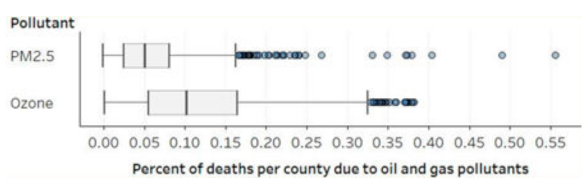
Abstract

Incomplete information regarding emissions from oil and natural gas production has historically made it challenging to characterize the air quality or air pollution-related health impacts for this sector in the United States. Using an emissions inventory for the oil and natural gas sector that reflects information regarding the level and distribution of $PM_{2.5}$ and ozone precursor emissions, we simulate annual mean $PM_{2.5}$ and summer season average daily 8 h maximum ozone concentrations with the Comprehensive Air-Quality Model with extensions (CAMx). We quantify the incidence and economic value of $PM_{2.5}$ and ozone health related effects using the environmental Benefits Mapping and Analysis Program (BenMAP). We find that ambient concentrations of $PM_{2.5}$ and ozone, and associated health impacts, are highest in a handful of states including Colorado, Pennsylvania, Texas and West Virginia. On a per-ton basis, the benefits of reducing $PM_{2.5}$ precursor emissions from this sector vary by pollutant species, and range from between \$6,300 and \$320,000, while the value of reducing ozone precursors ranges from \$500 to \$8,200 in the year 2025 (2015\$).

Graphical Abstract



INTRODUCTION

Air pollution health burden assessments often characterize the ambient levels of pollution and enumerate the adverse health outcomes associated with emissions from total anthropogenic sources or certain classes of industrial and mobile sectors.[1–4] Studies

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Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02050.
Additional details regarding: our approach for estimating population exposure and the health impact functions we applied(PDF)

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quantifying the economic value of these impacts have also reported estimates of the monetized benefits of reducing emissions that are precursors to fine particles (particulate matter sized 2.5 μm and smaller, that is, $PM_{2.5}$) from a given sector; these are often referred to as a "benefit per-ton."[5–7] This literature provides insight regarding the size, distribution, and economic value of the air pollution impacts associated with emissions from a broad array of industrial activities including industrial boilers, cement kilns and refineries among other sectors.[8]

While there is a growing literature examining air quality and human health impacts attributable to the oil and natural gas sector in the United States, we were unable to identify any studies employing a national emissions inventory coupled with a photochemical grid model to simulate the nonlinear formation of pollutants including ozone and $PM_{2.5}$ attributable to this sector.[9] Some studies have assessed the risks attributable to this sector within discrete geographic areas and employed less computationally complex air quality modeling approaches to monetize health impacts from oil and natural gas production nationwide.[10,11]

This work has been encumbered in part by limited data regarding the level and geographic distribution of emissions associated with oil and natural gas production across the U.S. As we describe below, emissions from this sector tend to originate from a large number of small but geographically diffuse sources located throughout several basins, making it challenging to estimate both the level and location of emissions accurately. These uncertainties, in turn, have made it difficult to simulate $PM_{2.5}$ and ozone air quality with confidence. In this paper, we apply an emissions inventory for the oil and natural gas sector that reflects a spatially detailed nationwide estimate of the level and distribution of emissions from this sector. This version of the U.S. Environmental Protection Agency's (EPA) National Emissions Inventory (NEI) for the year 2011 includes data that States provided as part of the process for developing the NEI; these data substantially improve our ability to characterize oil and natural gas emissions over space and time as compared to previous versions of the emissions inventory for these sources.

This improved inventory permits us to simulate of air quality impacts from this sector's emissions, with the goal of answering three key questions:

- What are the annual average $PM_{2.5}$ concentrations and summer season average daily 8-h maximum ozone concentrations associated with this sector?
- What is the human health burden—in terms of $PM_{2.5}$ and ozone-related premature deaths and illnesses—attributable to the oil and natural gas sector and how is this burden distributed over the U.S?
- What are the health benefits—in terms of avoided deaths and illnesses—of reducing $PM_{2.5}$ and ozone precursor emissions on a per ton basis and how does the benefit per ton (BPT) vary across pollutant precursor?

Below we describe our approach to modeling emissions and air quality before detailing our methodology for estimating the incidence and economic value of air pollution-attributable premature deaths and illnesses and calculating BPT values. We then present the results of this analysis before discussing the implications of this research.

MATERIALS AND METHODS

Estimating Emissions.

This analysis of the oil and natural gas sector draws upon estimates of pollutant emissions reported in the U.S. EPA NEI, which incorporates national activity, emission factors and basin-specific information submitted by State and Local agencies for this sector. Activity data are specific to each county for the year 2011. For the purposes of this analysis, we define the oil and natural gas sector as comprising an array of processes and equipment, including: drill rigs, workover rigs, well completions, well hydraulic fracturing, heaters, storage tanks, mud degassing, dehydration, pneumatics, well venting, fugitives, truck loading, wellhead engines, pipeline compressor engines, flaring, artificial lifts, and gas actuated pumps. These sources reflect the production and transportation of crude oil and natural gas and distribution of natural gas but exclude refineries and the distribution of refined products. The U.S. EPA defined the sector to reflect those activities covered by the New Source Performance Standards. Previous U.S. EPA analyses have assessed the air quality and health impacts associated with pollutants emitted during the refining process and so we exclude this sector here.[12]

Most oil and natural gas emissions data are estimated by county and spatially allocated to the model grid using surrogates that are based on year 2011 well locations and attributes related to the production of oil and natural gas and their byproducts. This procedure is described in the technical support document “Preparation of Emission Inventories for the Version 6.2, 2011 Emissions Modeling Platform”; the “platform” in this context describes the baseline inventory, meteorological model and air quality model used to simulate air quality.[13,14]

Beginning with this inventory, the U.S. EPA developed a method for estimating nonpoint emissions for the oil and natural gas production sector. In April of 2012, the Agency began collaborating with an extensive national workgroup comprised of state and regional emissions developers. This effort yielded a substantially improved Nonpoint Oil and Gas Emission Estimation Tool, which produces county-level emissions for calendar year 2011 for criteria pollutants and their precursors including volatile organic compounds and ammonia.[15] Both states and the U.S. EPA applied this tool to estimate emissions, either using the default tool inputs, or by providing their own basin- and/or county-specific inputs.

In brief, as part of a national outreach effort, U.S. EPA received data from two Regional Planning Organizations—the Lake Michigan Air Directors Consortium (representing Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) and the Mid-Atlantic Regional Air Management Association (representing 10 state and local agencies including the Allegheny County Air Quality Program, the Pennsylvania Department of Environmental Protection, the North Carolina Department of Natural Resources, the Virginia Department of Environmental Quality and the West Virginia Department of Environmental Protection). In total, the states submitting data included CA, CT, DC, DE, IA, ME, MI, NC, NE, NY, PA, OK, TX, UT, VA, WA. Each organization provided information including the location, emission rate and controls. VOC and $PM_{2.5}$ emissions are speciated based on basin-specific speciation factors provided by the Western Regional Air Partnership.[13,14] National VOC and $PM_{2.5}$ speciation profiles were used for this assessment where location speciation profiles were unavailable. Annual total emissions for this sector are evenly distributed across each hour of each day using temporal allocation factors that account for units operating continuously throughout the year.

To account for the expected change in the size and distribution of this sector over time, we projected the 2011 sector emissions to the year 2025 using economic growth factors based on product and consumption indicators derived from the Annual Energy Outlook (AEO) 2014 (Table 1).[13,14] We selected a future year of 2025 because it was most relevant for U.S. EPA air quality planning purposes. The AEO projected growth rates for each U.S. Census Division, which were then assigned to each basin. Projected levels of emissions from the sector can be useful to policy makers as they seek to understand the future air quality and health impacts attributable to the sector. However, as we note below, this procedure also introduces uncertainty to the analysis. Aside from the growth factors, emission reductions are reflected for some oil and natural gas categories including reductions of criteria air pollutants due to stationary reciprocating internal combustion engine regulations that reduce emissions of hazardous air pollutants and New Source Performance Standards. Additional details regarding our approach are available in the Version 6.2, 2011 Emissions Modeling Platform TSD.

Air Quality Modeling Simulations.

The Comprehensive Air-Quality Model with extensions (CAMx) version 6.20[16,17] was applied for the entire year of 2011 with a 10 day “spin-up” period at the end of 2010 to minimize the influence of initial conditions. The model domain covered the contiguous United States with 12 km by 12 km sized grid cells. The surface to model top (~15 km) was resolved with 25 layers with most in the boundary layer to best capture the diurnal variation in the surface mixing layer. CAMx has treatment of gas-phase chemistry based on Carbon Bond 6, inorganic particulate matter thermodynamics based on ISORROPIA, aqueous phase chemistry, and semivolatile partitioning of VOC to secondary organic aerosol.[16,18,19] In this assessment, CAMx was not modified to capture wintertime ozone formation that is associated with production activities in certain oil and natural gas basins, meaning the ozone air quality and health impacts provided here are entirely associated with traditional warm season (May 1 to September 30) ozone formation.[20,21] Moreover, the risk coefficients we used to quantify ozone effects were drawn from studies assessing the health risks associated with warm season ozone exposure; modeling ozone in this way ensures that the exposure estimates are consistent with the health impact assessment described below.

CAMx was applied with source apportionment to differentiate the contribution of the oil and natural gas sector from all other emissions. The contribution of oil and natural gas emissions was tracked to model estimated primary ($PM_{2.5}$ elemental carbon, $PM_{2.5}$ organic carbon, and crustal compounds) and secondary (e.g., ozone contributions from NO_x, ozone contributions from VOC, $PM_{2.5}$ sulfate ion, $PM_{2.5}$ nitrate ion, and $PM_{2.5}$ ammonium ion) pollutants.[16,22–24] The contribution of VOC emissions to secondary organic aerosol (SOA) were not tracked because the model estimates a very small amount of anthropogenic SOA (from all sources) and while this sector emits a large amount of VOC, the bulk of the species contributing to the emissions mass (e.g., methane, ethane, propane) are not known to yield large amounts of SOA. Year 2011 meteorological inputs were generated using the Weather Research and Forecasting model.[25] WRF was applied with a domain consistent with the photochemical grid model and has been shown to compare well with surface, upper air, and mixing layer height measurements.[26] Further details about the WRF configuration are provided in the Supporting Information. Initial chemical conditions and boundary inflow were extracted from a global model simulation using a database tool developed jointly by the University of Florida and the U.S. EPA, and subsequently translated to match the domain and chemical species employed for this assessment.[27] Both biogenic and anthropogenic emissions were incorporated into the air quality modeling. Biogenic emissions were estimated using the Biogenic Emission Inventory System version 3.6.1.[13,28,29] Anthropogenic emissions were based on the 2011 National Emission Inventory version 2 as described in the associated technical support document.[14,30] Wildland fire emissions were also included in the 2011 NEI version 2 and are based on known fires in 2011.[31]

Estimating Counts of Air Pollution-Related Deaths and Illnesses Attributable to the Oil and Natural Gas Sector.

We calculate a health impact function to quantify counts of premature deaths and illnesses attributable to the model-predicted $PM_{2.5}$ and ozone from the oil and natural gas sector. For each $PM_{2.5}$ and ozone human health end point we calculate a separate health impact function. Each function specifies four input parameters: (1) an effect coefficient (or, beta parameter) from a published air pollution epidemiology study; (2) a count of the number of people affected in each 12 km by 12 km air quality grid from the U.S. census; (3) the air quality concentration to which the population is exposed from the photochemical model; (4) a baseline rate of death or disease among this population from Centers for Disease Control and Prevention and the Agency for Healthcare Research and Quality.

To automate the procedure for calculating health impacts we used the open-source environmental Benefits Mapping and Analysis Program—Community Edition software program.[32] The $PM_{2.5}$-related health outcomes we quantify include premature death, respiratory hospital admissions, cardiovascular hospital admissions, emergency department visits for asthma, upper respiratory symptoms, lower respiratory symptoms, days of work lost, days of school lost, cases of aggravated asthma, and cases of acute respiratory symptoms. We quantify ozone-related end points including premature death, respiratory hospital admissions, respiratory emergency department visits, exacerbated asthma, and days of school missed.

Using the health impact function for $PM_{2.5}$-related deaths as an example, we specify the input parameters below. In eq 1, we estimated the number of $PM_{2.5}$-related total deaths (y_{ij}) for adults in each county j ($j = 1,\ldots,J$ where J is the total number of counties) as

$$y_j = \sum_a y_{ja} \tag{1}$$
$$y_{ija} = m0_{ja} \times \left(e^{\beta \cdot C_k} - 1\right) \times P_{ika},$$

where β is a beta coefficient for all-cause mortality in adults associated with annual average exposure to $PM_{2.5}$, $m0_{ja}$ is the baseline all-cause death rate for adults in county j stratified in 10-year age bins, C_k is the annual mean $PM_{2.5}$ concentration in air quality grid cell k, and P_{ka} is the number of adult residents in air quality grid cell k stratified into 5-year age bins. The program assigns the all-cause death rates for adults in county j to grid cell k using an area-weighting algorithm described in the BenMAP-CE user manual.[33] This health impact function returns a count of the number of $PM_{2.5}$-related deaths occurring in each county due to annual mean $PM_{2.5}$ concentrations. The function above can be generalized to the remaining $PM_{2.5}$ morbidity and ozone mortality and morbidity end points; when quantifying ozone-attributable premature deaths, we substituted a daily average mortality rate for the annual mortality rate noted above.

Our approach for specifying the health impact functions above is consistent with the methodology the U.S. EPA employed in the Regulatory Impact Analyses (RIAs) supporting the $PM_{2.5}$ and Ozone National Ambient Air Quality Standards (NAAQS).[34,35] These two RIAs considered evidence the Agency evaluated in the Integrated Science Assessments (ISAs) for Particulate Matter and Ozone. The ISAs systematically reviews the toxicological, epidemiological, and clinical evidence for each pollutant, carefully assessing the evidence before determining whether each pollutant is causally associated with a given health outcome. After identifying the human health end points as being either causally, or likely to be causally, associated with each pollutant, the RIA next evaluates the epidemiological studies quantifying these end points. As noted in the PM NAAQS RIA, the Agency "··· follow[s] a weight of evidence approach, based on the biological plausibility of effects, availability of concentration-response functions from well conducted peer-reviewed studies, cohesiveness of results across studies, and a focus on end points reflecting public health impacts···rather than physiological responses."[34] That RIA further specifies a host of criteria the Agency considers when selecting effect coefficients, including the study type, population attributes, pollutant measures, and other attributes.

To quantify PM-related premature deaths, we derived a long-term mortality β coefficient from a Hazard Ratio reported in the most recent extended analysis of the American Cancer Society (ACS) cohort (ages 30 and older) (β = 0.0058; SE =0.000962) (Supporting Information Table S-1).[36] To estimate ozone-related premature deaths, we derive a short-term mortality β coefficient from an estimate of the percentage increase in the risk of ozone-related death from a multicity analysis (ages 0–99) (β = 0.00051; SE = 0.00012) (Supporting Information Table S-2).[37]

As noted below, the dollar value associated with the incidence of air pollution-related deaths is considerable, and so we searched the literature to identify alternative concentration-response parameters from more recently published epidemiological studies. We were unable to identify a long-term epidemiological study of $PM_{2.5}$ all-cause mortality for a representative U.S. cohort of both adult males and females that was more current than Krewski et al. (2009).[36] However, as a sensitivity analysis, we also quantify risks using the hazard ratio from the extended analysis of the Harvard Six Cities study Lepuele et al. (2012); these results may be found in the Supporting Information (Table S-6).[38] We found that the Zanobetti & Schwartz (2008) ozone multicity study exhibited a number of strengths, including its evaluation of multiple exposure lags and its pooling of the single-city risk coefficients to derive a single national risk coefficient.[39] As a sensitivity analysis, we also report ozone-attributable premature deaths using the results of other broadly cited ozone mortality studies, including a multicity study (Table S-6).[40]

We performed a Monte Carlo-based simulation to construct an error distribution of estimated $PM_{2.5}$ and ozone-related effects. To inform the Monte Carlo simulation, we constructed a distribution around each effect (or, beta) coefficient using the standard error reported in each study; these resulting distributions are normally distributed (Table S-1). We calculated total numbers of premature deaths and illnesses in the contiguous U.S. for each year by summing the county-specific estimates, and report the sums of the 2.5th and 97.5th percentiles of the Monte Carlo distributions as 95% confidence intervals. As we note below, this distribution became an input to the Monte Carlo simulation we performed when quantifying a distribution of economic values. We use information regarding the distribution around each of the other input parameters (i.e., air quality, baseline incidence and population) and thus treated these parameters deterministically.

We defined m_{0ja} as the county-level age-stratified all-cause death rates from the Centers for Disease Control Wide-ranging Online Data for Epidemiologic Research database.[41] To account for the improved longevity of the population over time, we projected these death rates to future years using a life table reported by the U.S. Census Bureau (Supporting Information Tables S-3 and S-4). We defined the baseline incidence rates for the morbidity end points using rates of hospital admissions, emergency department visits and other outcomes for the year 2014 from the Healthcare Cost and Utilization Program (Supporting Information Table S-5). We defined P_{ka} using age-stratified population data from the U.S. Census Bureau. We projected population to year 2025 using an economic and demographic forecast from the Woods & Poole company.[42]

We calculated the fraction of all deaths due to $PM_{2.5}$ and ozone in each county and year using the following function:

$$\mathrm{AF}_j = \frac{y_j}{\sum_a m0_{ja} \times P_{ja}} \quad (2)$$

where y_j is the estimated number of air pollution deaths, $m0_{ja}$ is the age-stratified baseline death rate, and, P_{ja} is the age-stratified population, respectively, in county j.

We calculated the population-weighted annual mean concentration for all counties combined (C) as

$$C = \frac{\sum_j C_j \times P_j}{P} \quad (3)$$

where C_j is the county-average $PM_{2.5}$ concentrations in county j, P_j is the population in county j, and P is the total population over all counties combined.

Estimating Economic Values of Air Pollution Effects.

We estimate the economic value of the $PM_{2.5}$ and ozone-attributable premature deaths and illnesses on a per-ton of emissions basis using an approach that is consistent with the approaches used in the U.S. EPA's Ozone and PM NAAQS RIAs.[34] Those analyses applied a suite of willingness to pay (WTP) and cost of illness (COI) unit values built into the BenMAP-CE software that relate counts of adverse health outcomes to an estimated dollar value. A WTP measure describes the value that society places on avoiding some adverse health outcome. By contrast, COI reflects the direct costs associated with an adverse event; this can include medical expenses associated with a hospital visit and the value of lost productivity.

Because the value associated with air pollution-related premature deaths tends to account for as much as 99% of the total dollar value of a given air pollution health benefits assessment, it is worth detailing our method for valuing this end point. We apply a value of statistical life (VSL) to estimate the value of air pollution-related deaths. The VSL reflects the amount of money that a large number of people are willing to pay to reduce their risk of death by a small amount. As an example, 10 000 people might be willing to pay $500 to reduce their risk of death by 1-in-10 000; this yields a VSL of $5M. In this analysis, we apply a base VSL of $6.3 M in year 2000$ that is constant for all adult populations. This value is derived from a meta-analysis of 26 value of life studies published over a two-decade period.[43] While the number of publications reporting VSLs in the U.S. is quite large, we selected a value from this study because it has been applied extensively in the literature, making it easier to compare values in this manuscript to those published elsewhere.[2,6,44] The uncertainty around this mean value is represented by a Weibull distribution. We adjust this value in two ways. First, we inflate the VSL to year 2015$. Next, we account for the role of income growth in increasing future willingness to pay to reduce the risk of death by projecting the VSL to the year 2025. Adjusting the base VSL for these two factors yields a VSL of $10.4 M for the year 2025 in 2015$.

Benefit Per-Ton Calculation. We calculated the dollar per-ton for the contiguous United States BPT_i as

$$\mathrm{BPT}_p = \frac{\sum_{bp}}{\mathrm{emissions}_p} \quad (4)$$

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where BPT_p is the dollar benefit per ton for a given $PM_{2.5}$ or ozone precursor, b is the total dollar benefits summed across all health end points for precursor p and $emissions_p$ is the national sum of emissions for precursor p.

RESULTS

The CAMx model predicted annual mean $PM_{2.5}$ concentrations attributable to the sector ranging from a maximum of 5.27 $\mu g/m^3$ (located in western Colorado) to less than 0.001 μg/m3, with a median value of 0.04 $\mu g/m^3$ (Figure 1 and Table 2). States including Illinois, Ohio, and Pennsylvania in the east; Alabama, Louisiana, Oklahoma, and Texas in the south; North Dakota in the midwest; and Colorado and Wyoming in the west, experience the greatest $PM_{2.5}$ concentrations from the oil and natural sector (Figure 1). The predicted summer season average 8-h maximum ozone value ranges from a high of 8.12 ppb (located in Western Texas) to a low of 0.003 ppb, with a median value of 0.57 ppb (Figure 1 and Table 2). West Virginia in the east and Alabama, Louisiana, Nebraska, Oklahoma, and Texas in the south experience the greatest summer season ozone levels from this sector (Figure 1). The national population-weighted annual mean $PM_{2.5}$ value is about 0.05 $\mu g/m^3$ while the population-weighted summer season average 8 h maximum ozone value is1.34 ppb (Table 2).

For the year 2025, we estimate 970 (95% confidence interval 670–1300) ozone-related premature deaths and 1000 (95% confidence interval 520–1400) $PM_{2.5}$-related deaths nationwide (Table 2). We also estimate about 1000 respiratory and cardiovascular hospital admissions, 3600 emergency department visits, tens of thousands of upper and lower respiratory symptoms, approximately 100 000 lost work days, and over a million cases of exacerbated asthma and acute respiratory symptoms (Table S-6). Because the air quality impacts from this sector are spatially heterogeneous, we also report state-by-state estimates of PM and ozone-related premature deaths. The PM and ozone-related mortality burden is the in Texas, Pennsylvania, Ohio, Oklahoma, Illinois, California, Michigan, Colorado, Indiana, and Louisiana (Table 3). To account for the role of population size in influencing these values, we also report the number of PM and ozone-related deaths per 100 000 people, finding that Oklahoma, Louisiana, Colorado, Pennsylvania and Indiana experience the largest number of deaths on a population-normalized basis (Figure 2). Estimated dollar values for these cases of premature death range from $13 to $28 billion and cases of illnesses range from $1 to $200 million depending on the end point; full results may be found in Supporting Information Table S-7.

We also estimate the national BPT values for PM and ozone precursors by dividing the total estimated benefits associated with each ozone precursor or PM species by the tons emitted of that precursor. Modeled precursors of PM elemental and primarily emitted organic carbon (EC/OC), SO_2, and oxides of nitrogen (NO_x), and NO_x and VOC precursors were modeled for ozone. For the purposes of estimating the incidence attributable to each PM species, we assume that each specie is as detrimental to health as total PM mass. The two largest BPT estimate ranges were for the PM precursors to EC/OC and sulfate, at $140,000–$320,000 and $27,000–$62,000, respectively (2015$ for all estimates); this range reflects the sum of the value of the morbidity end points and the long-term PM mortality coefficients from

Krewski et al. 2009 at the low end and Lepeule et al. 2012 at the high end. The BPT ranges for the PM precursor to nitrate and the ozone precursor NO_x were of similar magnitudes, at \$2,800–\$6,300 and \$4,600–\$8,200, respectively. The range of economic value per ton of ozone-related VOC from the oil and natural gas sector was \$300–\$500; this range reflects the sum of the value of morbidity impacts and the Smith et al. 2009 ozone mortality risk coefficient at the low end and the Zanobetti & Schwartz 2008 risk coefficient at the high end.

DISCUSSION

The oil and natural gas sector emits pollutants that contribute to forming ozone and fine particles in the atmosphere, degrading air quality and ultimately adversely affecting public health in the form of premature deaths, hospital admissions, emergency department visits, cases of aggravated asthma, and lost days of school and work, among other outcomes.

While we were unable to identify other national-scale estimates of the air pollution impacts for this sector in the literature, we can place the estimates above in the context of analyses assessing the overall burden of $PM_{2.5}$ and ozone on health. The Global Burden of Disease study estimates about 100 000 $PM_{2.5}$ and ozone-related deaths in the United States for the year 2016.[4] A separate analysis of the U.S. reported about 130 000 $PM_{2.5}$ and ozone-related deaths for the year 2005.[45] The total number of oil- and natural gas-attributable $PM_{2.5}$ and ozone premature deaths represents a small fraction of the national burden these two analyses estimates. Because both the national burden analyses retrospectively estimate $PM_{2.5}$ and ozone-attributable deaths for 2010 and 2005, it is difficult to compare directly against these 2025-projected estimates. Moreover, neither national burden analyses reported state-by-state estimates of air pollution burden, which would arguably be a more relevant geographic unit of comparison for this sector, given the spatially heterogeneous air quality impacts from oil and natural gas facilities.

The results above indicate that the air quality and health impact associated with this sector correspond closely with the location of oil and natural gas facilities. Six states—Texas, Oklahoma, Colorado, North Dakota, West Virginia, and Pennsylvania—contributed almost 70% of the onshore natural gas production and over 74% of the onshore crude oil production in the lower 48 states in 2016.[46,47] These states also experience the highest levels of ground-level ozone and fine particle levels attributable to this sector. While the modeled ambient levels of fine particles are more spatially heterogeneous, ozone concentrations appear to be more spatially homogeneous across states including Nebraska, Oklahoma and Texas, suggesting a role for interstate transport. The estimated premature ozone and $PM_{2.5}$-related mortality corresponds well with the location of the air quality impacts. Indeed, in the western U.S., the sector tends to contribute $PM_{2.5}$ among locations in which fine particle levels are projected to be quite low—generally below about 6 $\mu g/m^3$. While we expect these areas to experience projected $PM_{2.5}$ levels well below the annual NAAQS of 12 $\mu g/m^3$, we quantify cases of excess $PM_{2.5}$-related premature deaths and illnesses in these locations because evidence suggests that there is no population-level concentration threshold for fine particles.

To our knowledge, this manuscript is the first reported benefit per-ton estimates for precursor emissions to $PM_{2.5}$ or ozone for the oil and natural gas sector derived from full-form photochemical grid modeling.[10] The $PM_{2.5}$-related health benefits of direct PM, sulfur dioxide (SO_2), and NO_x have previously been characterized for emission reductions from 17 industrial, area, and mobile emission sectors in the U.S. for the year 2016.[48] That manuscript published in 2012 did not quantify impacts from the oil and natural gas sector because of uncertainties associated with the 2005 emissions inventory for that sector. Direct PM BPT estimates for these 17 sectors range from $45,000–$490,000, which is comparable with our EC/OC BPT estimate of $140,000–$320,000. Similarly, our sulfate and nitrate BPT values ($27,000–$62,000 and $2,800– $6,300, respectively) fell within the range of SO_2 and NO_x BPT estimates for the 17 sectors ($12,000–$97,000 [with one exception: $400,000 for the iron and steel sector] and $1800– $16,000, respectively). As the BPT estimates presented here are comparable with previously published BPT values, we believe them to be reasonable.

Among all species and precursors considered in this study, the lowest BPT estimates were for VOC contributions to ozone formation (fewer than 100 deaths in 2025) than for NO_x (over 900 deaths each in 2025). In addition, there were considerably fewer restricted activity days, the health outcome with the second highest value, associated with VOC (under 170 000) than with NO_x (over 2 million). Another reason for less impact from VOC compared to NO_x is that most source areas tend to be located in places that are VOC-rich (also referred to as NO_x-sensitive) meaning that additional VOC has less impact than NO_x. This heterogeneity in ozone formation regime is reflected in the contribution results which is a strength of using a photochemical model to support ozone impact assessments.

Loomis and colleagues apply a suite of benefit per-ton values reported in the literature to quantify the air pollution impacts attributable to hydraulic fracturing in 14 states.[5,7,8] The authors calculate an average of these values, weighted according to whether the wells are located in urban or rural locations. The authors estimate the economic value of emissions from hydraulic fracturing of between $14 and $48B (2015$). Litovitz and colleagues quantify the economic value of air pollution impacts shale gas production in Pennsylvania, by employing the Air Pollution Experiments and Policy Analysis (APEEP) model.[7,11] This study estimates total damages of between $7.2 M and $32 M for Pennsylvania. While the present analysis did not report the total national economic value for the sector, multiplying the BPT values reported above against the sector emissions yields an estimate of between $13B to $29B, which is comparable to the value reported by Loomis et al.

Analyses of this scope and complexity are subject to important uncertainties and limitations. First, quantifying the air quality and health impacts for this sector is especially challenging because of uncertainties in the emission inventory for oil and natural gas production and transmission. These uncertainties can vary from basin to basin meaning that impacts in some areas may be better characterized than others depending on the level of effort provided by state and local agencies toward generating emissions and activity data for their particular area. The projected level of oil and natural gas production in 2025 is also sensitive to the price of oil in that year, which we cannot account for completely in this analysis. Further, uncertainties in the assumed composition of VOC emissions can be important, especially if the currently assumed composition is biased low for highly reactive VOC meaning less potential to facilitate ozone formation. We modeled an emissions inventory that was the best available at the time of the analysis and itself represented substantial improvements over previous inventories. Another uncertainty associated with quantifying an ozone-related BPT value in particular is that ozone-related impacts are sensitive to baseline levels of VOC and NO_x. These levels differ by location and are not assumed to change over time as these baseline pollutant levels change. Similarly, $PM_{2.5}$ impacts are sensitive to baseline levels of ammonia and in the case of nitrate ion also to favorable weather conditions (e.g., cool temperatures and higher relative humidity). $PM_{2.5}$ impacts from this sector are likely under-represented to some degree since impacts on SOA were not quantified. VOC emissions from this sector (e.g., aromatics) are known to form SOA and the NO_x emissions in proximity to biogenic VOC may also contribution to SOA formation.[49,50]

To the extent that future populations are healthier and more resilient to air pollution than we have forecast in this analysis, and thus more resilient to air pollution, then the BPT values may be overstated. The Monte Carlo analysis described above accounts only for the statistical uncertainty associated with the pollutant effect coefficients and economic unit values; it does not account for a host of other uncertainties associated with the emissions inventory, air quality modeling, baseline health or demographic information. Finally, the estimates of economic value are sensitive to the VSL that we applied; management policies affecting this sector.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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ABBREVIATIONS

BenMAP	environmental Benefits Mapping and Analysis Program
CAMx	Comprehensive Air Quality Model with extensions
EPA	Environmental Protection Agency
ICD	International Classification of Disease
MATS	Mercury and Air Toxics Standards
NAAQS	National Ambient Air Quality Standards
O_3	Ground-level ozone
$PM_{2.5}$	Particulate matter, 2.5 μm or less in diameter
RRF	Relative Response Factor

WHO World Health Organization

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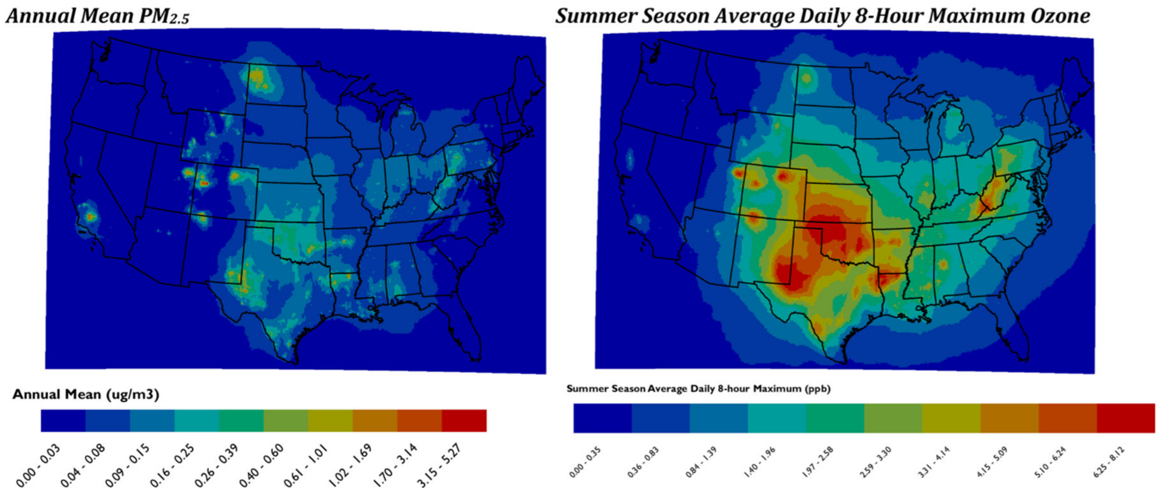

Figure 1.

Annual Mean $PM_{2.5}$ and Summer Season Daily 8 h Maximum Ozone Attributable to the Oil and Natural Gas Sector in 2025. State and county boundaries drawn according to Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line files in the ArcGIS software.

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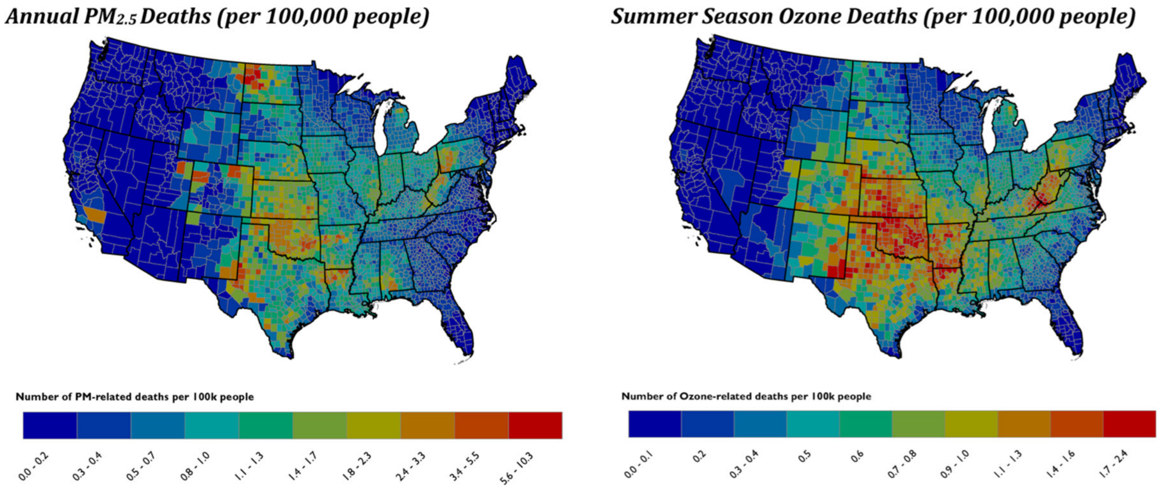

Figure 2.

Premature Deaths (per 100 000 people) attributable to annual mean $PM_{2.5}$ and Summer season daily 8 h maximum ozone from the oil and natural gas sector in 2025. State and county boundaries drawn according to Census Topologically Integrated Geographic Encoding and Referencing (TIGER)/Line files in the ArcGIS software.

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Table 1.

Emission Levels for the Oil and Natural Gas and All Other Sectors in 2025 (tons/year)

	pollutant					
	NO_x	SO_2	NH_3	CO	VOC	elemental and organic carbon
oil and gas	1 190 846	108 619	5927	978 765	3 671 787	10 451
biogenics	1 020 456			6 749 945	44 712 816	
fugitive dusts						51 370
residential wood combustion	34 805	7619	18211	2 328 506	408 910	208 118
industrial point sources	1 021 969	783 630	66 612	1 884 412	786 950	69 062
electricity generating units	2 021 937	2 089 206	46 238	907 624	42 253	23 149
area sources	75 462	95 102	94 938	278	3 426 185	212 672
wildland fires[a]	333 404	165 790	329 398	20 566 821	4 689 022	1 075 975

[a]Assumed constant from the 2011 baseline.

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Table 2.

Distribution of CAMx Model Predicted Annual Mean $PM_{2.5}$ and Summer Season 8-h Maximum Ozone Concentrations and Population-Weighted Levels for the Oil and Natural Gas Sector in 2025[a]

		percentile								
pollutant	**min**	**10%**	**25%**	**50%**	**75%**	**90%**	**max**	**mean**	**SD**	**national population-weighted value**
$PM_{2.5}$ (ug/m^3)	<0.01	0.0034	0.009	0.02	0.06	0.1	5.27	0.04	0.07	0.0557
SO_4	<0.01	0.001	0.004	0.008	0.016	0.03	0.55	0.013	0.015	0.02
NO_3	<0.01	<0.01	<0.01	<0.01	0.01	0.04	0.25	0.01	0.2	0.02
directly emitted $PM_{2.5}$	<0.01	<0.01	<0.01	<0.01	0.01	0.01	2	<0.01	0.02	<0.01
ozone (ppb)	<0.01	0.068	0.19	0.57	1.59	2.91	8.12	1.12	1.36	1.34
NO_x	<0.01	0.05	0.2	0.6	1.7	3	7.6	1.16	1.36	1.24
VOC	<0.01	<0.01	0.02	0.04	0.08	0.16	3.2	0.07	0.09	0.1

[a] Calculated from 12 × 12 km model predicted concentrations.

Table 3.

National-Total and Selected State $PM_{2.5}$-and Ozone-Related Premature Deaths Attributable to Emissions from the Oil and Natural Gas Sector in 2025

	estimated numbers of premature deaths (95% confidence interval)[b]			
state[a]	**attributable to $PM_{2.5}$**	**attributable to ozone**	**total deaths attributable to $PM_{2.5}$ and ozone**	**total deaths per 100 000 people**
Texas	130 (88—170)	130 (70—190)	260 (160—370)	1.4
Pennsylvania	85 (57—110)	55 (30—80)	140 (87—190)	1.6
Ohio	65 (44—86)	48 (26—70)	110 (69—160)	1.5
Oklahoma	48 (32—63)	55 (29—81)	100 (62—140)	4.1
Illinois	55 (37—73)	38 (20—55)	92 (57—130)	1.1
California	59 (40—77)	14 (7.4—20)	72 (47—97)	0.27
Michigan	39 (26—52)	32 (17—47)	71 (44—98)	1.1
Colorado	37 (25—49)	34 (18—49)	70 (43—98)	1.9
Indiana	38 (26—50)	29 (15—42)	66 (41—92)	1.6
Louisiana	34 (23—45)	28 (15—40)	61 (38—85)	2
national total	1000 (670—1300)	970 (520—1400)	1900 (1100—2700)	0.9

[a]These states comprise the largest health impacts for the sector. States listed by descending order of total $PM_{2.5}$ and ozone-attributable deaths.

[b]All values rounded to two significant figures.