ORIGINAL RESEARCH

QA1

QA2

Adverse Health Impacts of Outdoor Air Pollution, Including from Wildland Fires, in the United States

“Health of the Air,” 2018–2020

Kevin Cromar[1,2], Laura Gladson[1,2], Julia Gohlke[3], Yunyao Li[4], Daniel Tong[4,5], and Gary Ewart[6]

[1]Marron Institute of Urban Management, New York University, New York, New York; [2]New York University Grossman School of Medicine, New York, New York; [3]Environmental Defense Fund, Washington, DC; [4]Department of Atmospheric, Oceanic and Earth Sciences and [5]Center for Spatial Information Science and Systems, George Mason University, Fairfax, Virginia; and [6]American Thoracic Society, Washington, DC

ORCID IDs: 0000-0002-7745-2780 (K.C.); 0000-0002-0406-9684 (L.G.); 0000-0002-6984-2893 (J.G.); 0000-0002-3073-3227 (Y.L.); 0000-0002-4255-4568 (D.T.).

Abstract

Rationale: Adverse health impacts from outdoor air pollution occur across the United States, but the magnitude of these impacts varies widely by geographic region. Ambient pollutant concentrations, emission sources, baseline health conditions, and population sizes and distributions are all important factors that need to be taken into account to quantify local health burdens.

Objectives: To determine health impacts from ambient air pollution concentrations in the United States that exceed the levels recommended by the American Thoracic Society.

Methods: Using a methodology that has been well established in previous “Health of the Air” reports, this study provides policy-relevant estimates for every monitored county and city in the United States for the adverse health impacts of outdoor pollution concentrations using U.S. Environmental Protection Agency design values for years 2018–2020. Additionally, for the first time, the report includes adverse birth outcomes as well as estimates of health impacts specifically attributable to wildland fires using an exposure dataset generated through Community Multiscale Air Quality simulations.

Results: The adverse health burdens attributable to air pollution occur across the entire age spectrum, including adverse birth outcomes (10,660 preterm and/or low-weight births; 95% confidence interval [CI], 3,180–18,330), in addition to mortality impacts (21,300 avoidable deaths; 95% CI, 16,150–26,200), lung cancer incidence (3,000 new cases; 95% CI, 1,550–4,390), multiple types of cardiovascular and respiratory morbidity (748,660 events; 95% CI, 326,050–1,057,080), and adversely impacted days (52.4 million days; 95% CI, 7.9–92.4 million days). Two different estimates of mortality impacts from wildland fires were created based on assumptions regarding the underlying toxicity of particles from wildland fires (low estimate of 4,080 deaths, 95% CI, 240–7,890; middle estimate of 28,000 deaths, 95% CI, 27,300–28,700).

Conclusions: This year’s report identified sizable health benefits that would be expected to occur across the United States with compliance with more health-protective air quality standards such as those recommended by the American Thoracic Society. This study also indicates that a large number of excess deaths are attributable to emissions from wildland fires; air quality management strategies outside what is required by the Clean Air Act will be needed to best address this important source of air pollution and its associated health risks.

Keywords: air pollution; environmental policy; pregnancy outcome; risk assessment; wildfires

---

(Received in original form May 17, 2023; accepted in final form ■■■)

Supported by an Office of STEM Engagement Rapid Response Research Award, the Environmental Defense Fund of the National Aeronautics and Space Administration, the Marron Institute of Urban Management at New York University, and the American Thoracic Society.

Author Contributions: K.C.: conceptualization; methodology; writing, original draft; writing, review and editing; supervision; project administration; funding acquisition. L.G.: methodology; software; formal analysis; writing, original draft; writing, review and editing; visualization. J.G.: conceptualization; methodology; writing, original draft; writing, review and editing; supervision; project administration; funding acquisition. Y.L.: methodology; software; formal analysis; writing, review and editing. D.T.: conceptualization; methodology; software; resources; writing, review and editing; supervision. G.E.: writing, review and editing; project administration.

1 Correspondence and requests for reprints should be addressed to Kevin Cromar, Marron Institute of Urban Management, New York University, 370 Jay Street, 12th Floor, Brooklyn, NY 11201. E-mail: kevin.cromar@nyu.edu.

This article has a data supplement, which is accessible from this issue’s table of contents at www.atsjournals.org.

Ann Am Thorac Soc Vol ■■, No ■■, pp 1–12, ■■ ■■ 2023

DOI: 10.1513/AnnalsATS.202305-455OC
Internet address: www.atsjournals.org

This article serves as the fifth "Health of the Air" report, which has regularly provided updated estimates of the health impacts of outdoor air pollution at the local and national levels in the United States since it was first published in *AnnalsATS* in 2016 (1). The report is a joint effort between the American Thoracic Society (ATS) and environmental health researchers at New York University's Marron Institute of Urban Management. This year's report coincides with the U.S. Environmental Protection Agency (EPA) actively reviewing the National Ambient Air Quality Standards for fine particulate matter (i.e., <2.5 μm in diameter; $PM_{2.5}$) and ozone (O_3), both of which are evaluated in this report. Although health estimates are always included as part of the EPA's official review process, this report emphasizes not just the magnitude of effects at the national level but brings the focus much closer to home by providing estimates of adverse health impacts for increased levels of these pollutants for all cities and counties with a regulatory air quality monitor.

The general structure of the report has stayed largely the same, specifically in regard to quantifying the adverse health impacts across a range of health endpoints for ambient pollution concentrations greater than recommended by the ATS (8 $\mu g/m^3$ for long-term $PM_{2.5}$, 25 $\mu g/m^3$ for short-term $PM_{2.5}$, and 60 parts per billion [ppb] for O_3). At the same time, the report has also evolved by incorporating additional elements in each successive publication. Some of these previous improvements included adding estimates of incident lung cancer (1), looking at decadal trends (2), and providing updated health estimates based on a revision of the underlying recommendations from ATS (3). These efforts have not only provided evidence supporting broad calls for improved air quality standards at the federal level, but, perhaps more importantly, provided policy-relevant health information at the local level that can inform ongoing discussions on how to best prioritize and address unhealthy levels of outdoor air pollution at the local level.

This year's Health of the Air report includes two important improvements: the inclusion of health estimates specifically attributable to wildland fire emissions across the United States and the inclusion of preterm birth and low-birthweight outcomes as new health endpoints. Both of these advancements reflect a growing interest in one of the most important sources of outdoor air pollution in the United States and a recognition that increased levels of outdoor air pollution exert adverse health impacts throughout all stages of life, including before birth.

Wildland Fire Smoke

There is an increasing awareness of the important contribution of wildland fires to ambient pollution in the United States (4–6). Wildland fires (including wildfires, prescribed fires, and agricultural burns) constitute approximately 40% of primary $PM_{2.5}$ emissions and 25% of total $PM_{2.5}$ in the United States and dominate the interannual $PM_{2.5}$ variability (7, 8). Because of a combination of climate change (9–11) and a century of fire suppression (12), wildfire seasons are lengthening and increasing in intensity, producing emissions that may soon counteract decades of regional $PM_{2.5}$ reductions (13, 14). Primary pollutants emitted from wildland fires also contribute to the formation of downwind ground-level ozone (O_3), although conditions near fires may constrain O_3 formation (15, 16). Because the Clean Air Act's exceptional events rule excludes wildfire smoke from National Ambient Air Quality Standards attainment decisions, complete reliance on these standards cannot currently address issues of increasing adverse health impacts from wildland fires.

Adverse Birth Outcomes

Preterm birth and low birth weight are global health challenges that increase an infant's risk for numerous acute health risks, as well as increasing the lifelong risk of several chronic diseases (*see* Figure 1) (17–19). For example, diminished lung health is one of the most common long-term consequences of preterm birth (20, 21). Although treatments to enhance lung growth postnatally have increased the survival of infants born preterm, numerous studies suggest diminished lung function into adulthood (20, 22). Previous studies have defined the positive relationship between ambient air pollution exposure ($PM_{2.5}$ and O_3) and the risks of preterm birth and low birth weight (23–25). Regarding periods of susceptibility, it is thought that chronic exposure to air pollution throughout pregnancy results in reduced oxygen and nutrients, causing intrauterine growth restriction and low birth weight (26, 27), and more acute exposures can additionally increase the risk of the initiation of labor and premature rupture of membranes, leading to an increased risk of preterm birth (Figure 1) (28). These adverse birth outcomes are not presently accounted for in regulatory impact assessments for $PM_{2.5}$ or ozone, although previous evaluations suggest substantial economic damages from these effects (29–31).

Methods

This study uses a methodological structure described in previous Health of the Air reports (1–3, 32) with updates reflecting the latest epidemiological research. These methods largely follow those used by the EPA in its regulatory review processes, with additional details described herein.

Daily $PM_{2.5}$ and O_3 concentrations were retrieved from the EPA Air Quality System for all monitored counties in the United States, defined as those with valid design values for 2018–2020. Design values are a statistic used by the EPA to define county-level air quality and determine whether locations are in compliance with federal regulatory levels (33). Design values are based on the 3-year average of the annual mean concentrations for long-term $PM_{2.5}$, the 24-hour 98th percentile concentration for short-term $PM_{2.5}$, and the 3-year average of the fourth-highest daily 8-hour maximum concentration for O_3. From these values, baseline and control datasets for each county were created using a 24-hour metric for $PM_{2.5}$ and an 8-hour maximum metric for O_3. The pollution increment considered in this health analysis corresponds to the difference between design values (12 $\mu g/m^3$ for long-term $PM_{2.5}$, 35 $\mu g/m^3$ for short-term $PM_{2.5}$, and 70 ppb for O_3) and ATS-recommended standards (8 $\mu g/m^3$ for long-term $PM_{2.5}$, 25 $\mu g/m^3$ for short-term $PM_{2.5}$, and 60 ppb for O_3).

County-level baseline incidence information for respiratory and all-cause mortality was obtained from the National Center for Health Statistics Mortality Data on the Centers for Disease Control and Prevention's Wide-ranging Online Data for Epidemiologic Research database (34), with other incidence numbers derived from the EPA's Environmental Benefits Mapping and Analysis Program Community Edition

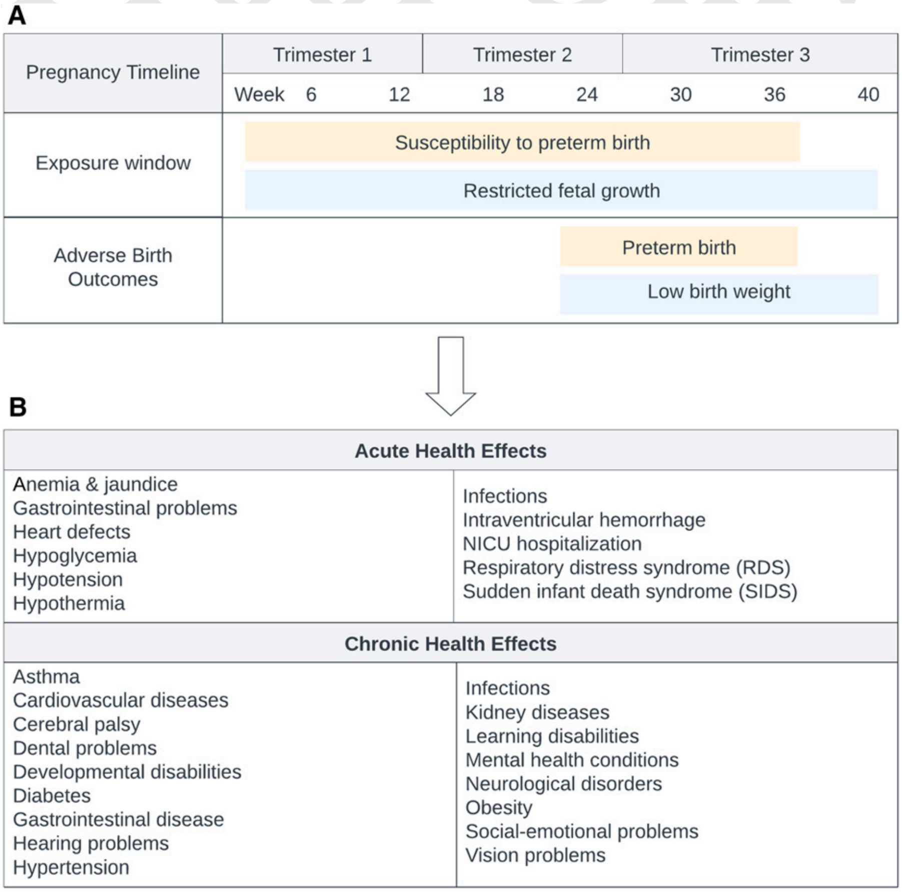

Figure 1. Clinical significance of air pollution–driven adverse birth outcomes. (*A*) How the timing of air pollution exposure during pregnancy effects the risk of the adverse birth outcomes included in this analysis. Specifically, exposure from weeks 1 to 37 increases the susceptibility to preterm birth, defined as birth between weeks 25 and 36; exposure throughout pregnancy restricts fetal growth, which can result in low birth weight of preterm and full-term births. (*B*) Acute and chronic health risks following preterm and low-weight births (17–19, 28). 8

(version 1.5) (35). Each of these endpoints used baseline incidence data from 2019 to avoid the confounding effects of coronavirus disease (COVID-19) on respiratory hospitalizations and deaths in 2020. County-level baseline incidence data (2018–2020) for preterm births and low-weight births were acquired from the Centers for Disease Control and Prevention's National Center for Health Statistics natality public-use files (36). Three-year incidence values were obtained and averaged to annual counts for this endpoint to reduce the frequency of suppressed counts in counties with low totals.

The EPA's Environmental Benefits Mapping and Analysis Program Community Edition was used to conduct county-level health impact assessments of the delta between current air pollution levels and those recommended by the ATS. Health impact functions (also called concentration–response functions) represent the relationship between pollutant concentration changes and specific health outcomes based on risk values derived from the epidemiological literature (37). This study uses health impact functions specifically designated as EPA "standard health functions" (updated in 2020) to calculate county-level health impacts of pollution levels exceeding ATS recommendations (Table E1 in the online supplement lists all the studies used). Health functions for O_3-associated preterm birth were derived from the study of Rappazzo and coworkers (23), which compiled results across 19 cohort and case-control studies. Health functions for O_3-related low birth weight were derived from the study of Li and coworkers (24), a meta-analysis of 14 cohort studies. For $PM_{2.5}$-associated preterm birth, we used summary effect values from a recent meta-regression (25) that included 40 separate studies for each outcome. For $PM_{2.5}$-associated low-birthweight health functions, the studies of Ghosh and coworkers (25) and Li and coworkers (24), which also conducted a meta-analysis across 29 studies, were coupled using fixed effects pooling.

This year's report includes an additional analysis of the health impacts of air pollution from wildland fire pollution in all counties in the contiguous United States using high-resolution, satellite-derived wildland fire smoke exposure data (38). Using a blended Moderate-Resolution Imaging Spectroradiometer and Visible Infrared Imaging Radiometer Suite fire detection product, two Community Multiscale Air Quality simulations with and without fire emissions were performed to produce high-resolution $PM_{2.5}$ predictions for the contiguous United States. The Community Multiscale Air Quality estimates align well with urban and rural area ground measurements, making it an ideal model for nationwide analysis (39). In this study, daily with- and without-fire concentrations of $PM_{2.5}$ (24-h mean) and O_3 (8-h max) were aggregated to the county level using area-weighted analysis for 2020. Health functions for mortality risks for wildland fires were estimated using standard (40, 41) and wildland fire–specific health functions (42). The pollution increment considered in the wildland fire health impact assessment corresponds to the difference between daily pollutant predictions from the with-fire and without-fire models.

Results

Of the 3,144 total counties in the contiguous United States, there were 515 with valid $PM_{2.5}$ monitoring data, with 210 exceeding the ATS recommendation for long-term $PM_{2.5}$ (8 μg/m^3) and 101 exceeding the recommendation for short-term $PM_{2.5}$ (25 μg/m^3); 75 counties exceeded both. Of the 693 counties with valid O_3 data, 487 exceeded the ATS recommendation (60 ppb).

Preventable national annual health
2 impacts associated with $PM_{2.5}$ (Table 1) and O_3 (Table 2) greater than the ATS recommended levels in monitored U.S. counties include 13,900 deaths (95% confidence interval [CI], 13,500–14,300) for $PM_{2.5}$ and 7,400 deaths (95% CI, 2,650–11,900) for O_3, 3,000 new cases of lung cancer (95% CI, 1,550–4,390) attributable to $PM_{2.5}$, 748,660 (95% CI, 326,050–1,057,080) cardiovascular and respiratory morbidities combined for $PM_{2.5}$ and O_3, 52.4 million (95% CI, 7.9–92.4 million) adversely impacted days combined for $PM_{2.5}$ and O_3, and 10,660 (95% CI, 3,180–18,330) adverse birth outcomes. Because health estimates are based on the pollution increment between the ATS recommendations and the current county pollution levels (design values), these estimates represent the health outcomes that could have been prevented if all counties in the United States met the ATS recommendations between 2018 and 2020. Mortality totals reported here include all causes of death based on the work of Di and coworkers (40) for $PM_{2.5}$ and that of
3 Katsouyanni and coworkers (43) for O_3; however, results from other mortality studies used in EPA assessments are also included in Tables 1 and 2. Individual county design values and health outcomes are provided in Table E2 in the data supplement. Because of the low 5-year survival rates of 26% for non–small-cell and 7% for small-cell lung cancer (44), these are grouped with the mortality health endpoints in the tables in this report.

Across monitored U.S. counties, 4,400 preterm (95% CI, 1,590–7,410) and 6,270 low-weight (95% CI, 1,590–10,930) births each year are associated with air pollution levels greater

Table 1. Preventable national annual health impacts from $PM_{2.5}$ greater than American Thoracic Society recommendations (2019)

Health Endpoint	Annual Preventable Health Impacts
Mortality*	
All-cause (40)	13,900 (13,500 to 14,300)
All-cause (41)	20,400 (13,700 to 26,800)
Lung cancer diagnosis	3,000 (1,550 to 4,390)
Morbidity	
Acute myocardial infarction	1,120 (530 to 1,680)
Emergency room visits	
Cardiovascular	3,320 (−1,280 to 7,740)
Respiratory	7,630 (1,500 to 15,870)
Hospital admissions	
Cardiovascular	1,210 (−8,390 to 6,010)
Neurological	3,580 (2,680 to 4,350)
Respiratory	220 (10 to 420)
New onset asthma and hay fever/rhinitis	234,080 (66,410 to 347,250)
Out-of-hospital cardiac arrest, stroke	780 (270 to 1,140)
Adversely impacted days	
Acute respiratory symptoms	10,300,000 (8,350,000 to 12,100,000)
Asthma symptoms (albuterol use)	4,720,000 (−2,310,000 to 11,400,000)
Work loss days	1,760,000 (1,480,000 to 2,020,000)
Adverse birth outcomes	
Low birth weight	1,880 (1,090 to 2,740)
Preterm birth	3,150 (1,590 to 4,920)

Definition of abbreviation: $PM_{2.5}$ = fine particulate matter <2.5 μm in diameter.
Data in parentheses are 95% confidence intervals. Only counties in the contiguous United States with a design value and consistent monitoring data in 2019 are included in this analysis (*n* = 515). Suppressed low counts of adverse birth outcomes resulted in a smaller subset of counties assessed for this endpoint (*n* = 327).
*Individual study results are reported for mortality impacts due to key differences in their methodologies.

Table 2. Preventable national annual health impacts from ozone above American Thoracic Society recommendations (2019)

Health Endpoint	Annual Preventable Health Impacts
Mortality*	
All-cause (43)	7,400 (2,650 to 11,900)
Respiratory (41)	6,730 (4,730 to 8,610)
Morbidity	
Emergency room visits, respiratory	30,940 (8,550 to 64,210)
Hospital admissions, respiratory	1,190 (−310 to 2,640)
New-onset asthma and hay fever/rhinitis	464,600 (256,090 to 605,780)
Adversely impacted days	
Acute respiratory symptoms	9,720,000 (3,930,000 to 15,200,000)
Asthma symptoms	19,100,000 (−2,490,000 to 38,300,000)
School loss days	6,800,000 (−1,030,000 to 13,400,000)
Adverse birth outcomes	
Low birth weight	4,390 (500 to 8,190)
Preterm birth	1,250 (0 to 2,490)

Data in parentheses are 95% confidence intervals. Only counties in the contiguous United States with a design value and consistent monitoring data in 2019 are included in this analysis (*n* = 692). Suppressed low counts of adverse birth outcomes resulted in a smaller subset of counties assessed for this endpoint (*n* = 415).
*Individual study results are reported for mortality impacts as a result of key differences in their methodologies.

than the ATS recommendations (Tables 1 and 2). A total of 72% of air pollution–related preterm births are associated with $PM_{2.5}$, and 70% of low-weight births are associated with O_3. Comparing across monitored metropolitan areas, the highest annual adverse birth outcome counts associated with ambient air pollution occur in Los Angeles and Riverside, CA; Houston, TX; Chicago, IL; and Phoenix, AZ (Tables 3 and 4).

The top 25 cities with the most to gain by meeting ATS recommendations, shown in Tables 3 and 4, were determined by ranking cities by all-cause mortality counts. The cities with the greatest adverse health impacts from air pollution are Los Angeles, CA, with approximately 3,300 (95% CI, 2,470–4,080) mortalities per year, followed by Riverside, CA (1,900; 95% CI, 1,460–2,310); Chicago, IL (985; 95% CI, 759–1,200); and Phoenix, AZ (802; 95% CI, 581–1,200).

Daily $PM_{2.5}$ levels from wildland fires are compared spatially in counties with and without federal ground monitors in Figure 2. $PM_{2.5}$ from wildland fires is ubiquitous across the United States and may not be fully captured by existing ground monitors, with annual averages of exposures reaching $\geqslant 1\ \mu g/m^3$ in 32% of all counties (981 of 3,109). In the southern United States, 34% of counties (484 of 1,421) experience $\geqslant 1\ \mu g/m^3$ of fire $PM_{2.5}$ on any given day, and the vast majority of these are unmonitored (86%), including all counties in the top 1% of exposure concentration. Half of the counties in the western United States (50 of 104) experiencing an average of $>4\ \mu g/m^3$ of fire $PM_{2.5}$ per day are also unmonitored.

Table 5 summarizes regional fire $PM_{2.5}$ concentrations and populations by count monitoring status. Across the nation, fire $PM_{2.5}$ makes up approximately 16% of total ambient $PM_{2.5}$ over the entire year, with a daily average of $1.6\ \mu g/m^3$. This fraction varies by region and constitutes 44% in the western United States, averaging $4.6\ \mu g/m^3$ each day. In the southern and midwestern regions, where approximately 60% of the U.S. population lives, nearly 10% of ambient $PM_{2.5}$ comes from wildland fires year-round.

Preventable national annual (2019) health impacts associated with wildland fire $PM_{2.5}$ (Table 6) and O_3 (Table 7) in all contiguous U.S. counties total approximately 28,000 deaths (95% CI, 27,300–28,700) for $PM_{2.5}$ and 828 deaths (95% CI, 295–1,340) for O_3, 5,910 new cases of lung cancer (95% CI, 3,080–8,600) attributable to $PM_{2.5}$, 474,840 (95% CI, 149,870–700,140)

Table 3. Top 25 cities with the most to gain by meeting American Thoracic Society recommendations for $PM_{2.5}$ (2019)

Rank	City Region	Annual $PM_{2.5}$-Attributable Health Impacts				
		Mortality	Lung Cancer Diagnosis	Adverse Birth Outcomes	Morbidity	Adversely Impacted Days
1	Los Angeles (Long Beach–Glendale), CA	2,086 (2,031–2,140)	390 (203–567)	740 (395–1,125)	40,896 (9,770–62,279)	2,945,090 (1,397,246–4,414,398)
2	Riverside (San Bernardino–Ontario), CA	1,269 (1,235–1,302)	232 (122–336)	469 (251–711)	26,032 (6,473–39,400)	1,658,884 (705,749–2,559,216)
3	Chicago (Naperville–Arlington Heights), IL	662 (644–679)	182 (94–268)	259 (138–396)	11,424 (2,812–17,598)	788,988 (372,568–1,187,332)
4	Phoenix (Mesa–Scottsdale), AZ	480 (467–493)	107 (55–158)	151 (80–232)	8,261 (2,022–12,676)	536,149 (239,419–819,764)
5	Sacramento (Roseville–Arden–Arcade), CA	465 (453–477)	100 (52–146)	137 (73–209)	7,647 (1,856–11,625)	512,416 (229,004–780,891)
6	Anaheim (Santa Ana–Irvine), CA	460 (448–472)	93 (48–136)	127 (67–194)	8,404 (2,125–12,770)	592,643 (279,331–891,471)
7	Houston (The Woodlands–Sugar Land), TX	408 (397–418)	101 (52–148)	310 (164–474)	12,273 (3,131–18,825)	764,772 (323,639–1,186,754)
8	Bakersfield, CA	355 (345–364)	66 (35–95)	172 (93–258)	8,800 (2,262–13,079)	526,310 (201,753–829,415)
9	Fresno, CA	349 (340–358)	59 (31–85)	155 (83–234)	7,567 (1,900–11,298)	455,677 (175,183–719,427)
10	Oakland (Hayward–Berkeley), CA	338 (328–346)	73 (37–108)	111 (59–170)	6,254 (1,549–9,543)	451,175 (216,097–675,769)
11	Pittsburgh, PA	333 (324–341)	81 (41–119)	63 (33–96)	2,960 (659–4,596)	216,336 (108,471–319,085)
12	Detroit (Dearborn–Livonia), MI	327 (318–336)	89 (46–131)	126 (67–192)	4,522 (995–6,998)	286,704 (125,603–440,430)
13	San Diego (Carlsbad), CA	263 (256–270)	54 (28–80)	85 (45–130)	4,712 (1,162–7,227)	334,597 (160,513–501,544)
14	San Jose (Sunnyvale–Santa Clara), CA	262 (255–269)	59 (30–86)	103 (55–157)	6,006 (1,490–9,123)	434,913 (205,045–653,729)
15	Las Vegas (Henderson–Paradise), NV	208 (202–214)	0	80 (42–122)	3,285 (788–5,059)	228,973 (108,339–344,428)
16	Modesto, CA	203 (198–209)	39 (20–56)	65 (35–98)	3,753 (883–5,713)	226,866 (92,308–352,906)
17	Stockton (Lodi), CA	203 (198–209)	41 (21–60)	81 (43–123)	4,249 (1,096–6,417)	249,267 (99,916–389,573)
18	Cincinnati, OH/KY/IN	185 (180–189)	53 (27–78)	63 (33–96)	2,507 (607–3,841)	162,533 (72,219–248,617)
19	Philadelphia, PA	176 (171–181)	50 (25–74)	57 (30–87)	2,456 (581–3,778)	164,119 (76,477–248,001)
20	Visalia (Porterville), CA	173 (169–178)	26 (14–37)	85 (46–128)	4,423 (1,148–6,593)	247,855 (87,165–398,422)
21	Redwood City–South San Francisco, CA	173 (168–177)	42 (21–61)	48 (25–73)	2,432 (564–3,753)	224,466 (124,944–319,649)
22	Indianapolis (Carmel–Anderson), IN	167 (163–171)	55 (28–81)	88 (47–134)	2,985 (737–4,512)	196,725 (85,693–302,578)
23	Medford, OR	160 (155–164)	31 (16–45)	22 (12–33)	1,322 (319–2,000)	89,765 (40,556–135,709)
24	Portland (Vancouver–Hillsboro), OR/WA	141 (137–145)	31 (16–45)	35 (18–54)	2,427 (600–3,716)	161,395 (72,768–245,911)
25	Seattle (Bellevue–Everett), WA	138 (135–142)	36 (18–54)	45 (24–70)	2,620 (665–4,023)	190,926 (93,020–284,905)

For definition of abbreviations, *see* Table 1.
Data in parentheses are 95% confidence intervals. Annual excess air pollution–related health impacts are derived from 2018–2020 U.S. Environmental Protection Agency design values and aggregated by core-based statistical area or metropolitan division. Rank values are based on all-cause mortality counts from Di and coworkers (40).

cardiovascular and respiratory morbidities combined for $PM_{2.5}$ and O_3, 27.5 million (95% CI, 9.7–42.0 million) adversely impacted days combined for $PM_{2.5}$ and O_3, and 7,310 (95% CI, 3,730–11,260) adverse birth outcomes. Mortality totals reported here are based on all causes of death based on the work of Di and coworkers (40) for $PM_{2.5}$ and the work of Katsouyanni and coworkers (43) for O_3. However, the estimate of mortality impacts from wildland fire $PM_{2.5}$ varies dramatically when using standard health functions versus wildland fire–specific health functions (4,080 deaths; 95% CI, 242–7,890), although these wildland fire–specific functions are relatively scarce and have yet to be fully articulated. State-level $PM_{2.5}$-associated annual mortalities are compared between standard and wildland fire–specific health functions in Table 8.

Discussion

The EPA is currently (as of 2023) reviewing the federal air quality standards for $PM_{2.5}$ and O_3. These reviews not only take into account the scientific evidence of the adverse health impacts of outdoor air pollution, but also include exposure and risk assessments that show the potential impacts of various policy decisions. In reviewing this evidence, the ATS has recommended that the EPA adopt revised standards for $PM_{2.5}$ (8 μg/m^3 annual; 25 μg/m^3 daily) and O_3 (60 ppb daily) (3). This report provides policy-relevant health estimates for ambient pollution concentrations greater than these recommended levels. These estimates are not only provided at the national level, showing the profound health benefits that would occur if these recommendations were adopted, but also at the local level to provide a meaningful context for air quality management decisions made by counties, cities, and states.

Air pollution–related health risks are not only driven by ambient pollution exposures and baseline health risks, but can also reflect the size and distribution of the exposed population. For example, the ranking of cities with the most to gain by meeting ATS recommendations (shown in Tables 3 and 4) shows that Houston, TX, has the sixth and seventh highest mortality impacts for O_3 and $PM_{2.5}$, respectively, but is ranked third for the most air pollution–related preterm birth outcomes. Overall, the cities with the most to gain by

Table 4. Top 25 cities with the most to gain by meeting American Thoracic Society recommendations for ozone (2019)

Rank	City Region	Annual Ozone-Attributable Health Impacts			
		Mortality	Adverse Birth Outcomes	Morbidity	Adversely Impacted Days
1	Los Angeles (Long Beach–Glendale), CA	1,208 (434–1,944)	850 (76–1,577)	81,183 (43,702–108,198)	6,331,382 (113,802 to 11,406,036)
2	Riverside (San Bernardino–Ontario), CA	628 (226–1,009)	474 (42–876)	45,474 (24,769–60,786)	3,352,223 (−7,677 to 6,042,116)
3	Chicago (Naperville–Arlington Heights), IL	323 (115–522)	257 (22–489)	20,747 (10,932–28,432)	1,505,220 (27,042 to 2,852,944)
4	Phoenix (Mesa–Scottsdale), AZ	322 (114–520)	235 (20–445)	22,415 (11,990–30,249)	1,567,737 (12,824 to 2,950,264)
5	New York (Jersey City–White Plains), NY/NJ	291 (103–471)	237 (21–453)	19,077 (9,972–26,249)	1,395,885 (35,565 to 2,662,401)
6	Houston (The Woodlands–Sugar Land), TX	204 (74–329)	286 (24–545)	20,985 (11,113–28,625)	1,418,634 (−140 to 2,707,715)
7	San Diego (Carlsbad), CA	200 (71–324)	148 (13–281)	14,215 (7,628–19,006)	1,019,392 (20,699 to 1,911,679)
8	Anaheim (Santa Ana–Irvine), CA	183 (65–297)	121 (10–230)	13,873 (7,520–18,622)	958,164 (17,610 to 1,799,818)
9	Dallas (Plano–Irving), TX	146 (53–236)	164 (14–314)	13,983 (7,376–19,157)	999,046 (5,273 to 1,910,006)
10	Denver (Aurora–Lakewood), CO	123 (44–199)	115 (10–219)	9,134 (4,885–12,345)	689,207 (11,292 to 1,301,038)
11	Las Vegas (Henderson–Paradise), NV	121 (43–195)	100 (8–191)	7,014 (3,693–9,506)	534,748 (10,406 to 1,010,503)
12	Sacramento (Roseville–Arden–Arcade), CA	105 (37–170)	61 (5–117)	6,449 (3,432–8,708)	466,616 (5,863 to 887,625)
13	Warren (Troy–Farmington Hills), MI	105 (37–170)	61 (5–116)	5,333 (2,792–7,319)	360,121 (8,379 to 684,958)
14	St. Louis, MO/IL	102 (36–165)	70 (6–135)	5,451 (2,870–7,463)	366,653 (5,220 to 702,392)
15	Fort Worth (Arlington), TX	98 (35–158)	98 (8–187)	8,044 (4,258–10,996)	560,380 (1,018 to 1,070,248)
16	Bakersfield, CA	92 (33–148)	85 (7–160)	7,864 (4,214–10,600)	563,260 (−8,360 to 1,043,243)
17	Philadelphia, PA	87 (31–141)	84 (7–161)	4,937 (2,582–6,770)	372,582 (5,656 to 710,427)
18	Cincinnati, OH/KY/IN	82 (29–133)	61 (5–116)	4,986 (2,627–6,795)	327,427 (2,687 to 626,076)
19	Cleveland (Elyria), OH	81 (28–132)	51 (4–98)	3,655 (1,916–5,011)	243,614 (4,607 to 465,055)
20	Detroit (Dearborn–Livonia), MI	77 (27–125)	75 (6–144)	4,345 (2,293–5,950)	286,612 (1,599 to 550,257)
21	Montgomery County (Bucks County–Chester County), PA	75 (26–122)	28 (2–55)	3,342 (1,744–4,595)	252,881 (5,478 to 482,140)
22	Fresno, CA	74 (26–119)	66 (5–125)	5,742 (3,102–7,644)	431,641 (−5,955 to 814,848)
23	Baltimore (Columbia–Towson), MD	72 (25–116)	46 (4–88)	3,848 (2,030–5,252)	274,440 (4,594 to 524,556)
24	Nassau County (Suffolk County), NY	63 (22–102)	36 (3–69)	3,455 (1,840–4,666)	246,366 (5,349 to 468,961)
25	Pittsburgh, PA	63 (22–102)	25 (2–49)	2,164 (1,121–2,996)	167,860 (5,160 to 320,042)

For definition of abbreviations, *see* Table 1.
Data in parentheses are 95% confidence intervals. Annual excess air pollution-related health impacts are derived from 2018–2020 U.S. Environmental Protection Agency design values and aggregated by core-based statistical area or metropolitan division. Rank values are based on all-cause mortality counts from Katsouyanni and coworkers (43).

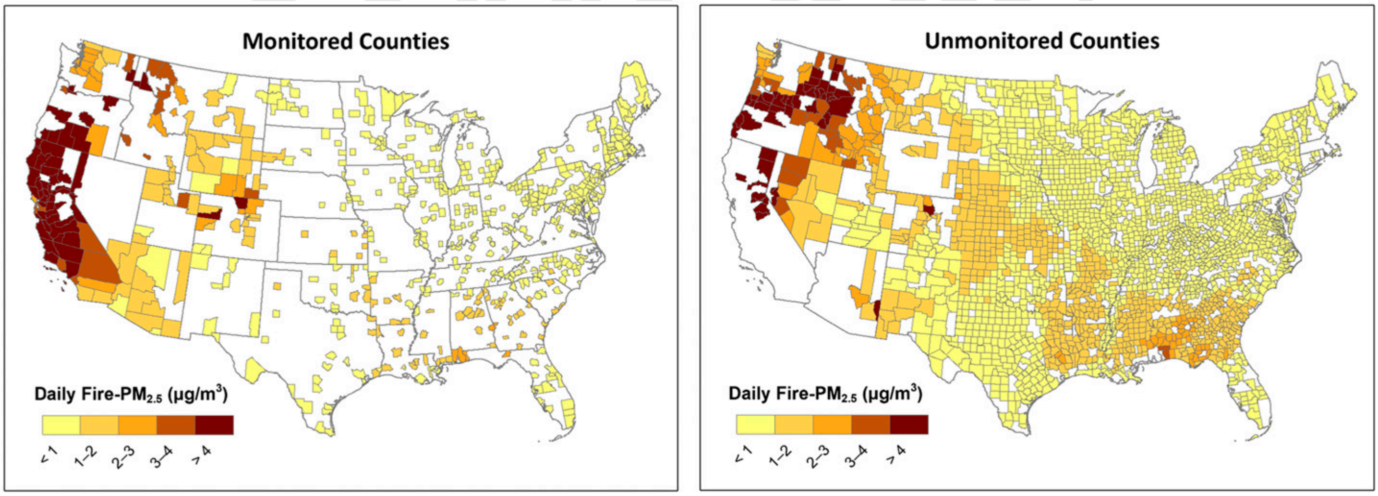

Figure 2. Annual means of daily fine particulate matter <2.5 μm in diameter from wildland fires in counties with and without federal ground monitors (2020). $PM_{2.5}$ = fine particulate matter <2.5 μm in diameter.

improving ambient air quality to the levels recommended by the ATS have high pollution concentrations and large exposed populations.

Although most attention is often focused on the mortality impacts of outdoor air pollution, other health endpoints are often more profoundly felt at the individual level. This report estimates that there are hundreds of thousands of cases of new-onset asthma and rhinitis due to $PM_{2.5}$ and O_3 exposures. This is in line with a recent ATS report that concluded that air pollution not only worsens the health conditions for those who already have respiratory disease, but can lead to the new onset of disease as well (45).

Adverse Birth Outcomes

Specifically in regard to the results for adverse birth outcomes, based on current evidence, exposure to $PM_{2.5}$ is more strongly associated with preterm birth, whereas exposure to ozone is more strongly associated with low birth weight. These differences could reflect different mechanisms of action. For example, placental-mediated toxicity may be greater for $PM_{2.5}$ (46), whereas oxidative stress mechanisms leading to fetal growth restriction may be the primary mechanism associated with ozone-related low birth weight (47). Additionally, exposure duration and variation across the pregnancy period in the underlying epidemiological analysis could also influence the derived concentration–response relationships for these outcomes.

Our results are comparable to those of other studies that have investigated the associations of preterm births with particulate matter pollution in the United States (29–31). Overall, the magnitude of impact due to this health endpoint provides strong supporting evidence in favor of including preterm birth in future EPA health assessments of air pollution. The Health of the Air report has a history of including estimates for health endpoints with growing epidemiological evidence supporting their associations with air pollution, but these are not included in EPA regulatory impact assessments, such as a previous version of the report that provided estimates of the impact in terms of new cases of lung cancer (1). The EPA has since incorporated lung cancer health functions in its assessments, and may benefit from the inclusion of preterm births to provide a more comprehensive assessment of overall health burden.

Impacts from Wildland Fires

This year's report uses a novel dataset of satellite-based and modeled wildland fire pollutant concentrations to quantify the health impacts associated with smoke exposure across the contiguous United States (38). This is an improvement on much of the existing literature, which estimates health impacts from wildland fires based on binary

Table 5. Regional wildland fire $PM_{2.5}$ concentrations and populations by county monitoring status (2020)

	Population in Millions (% of U.S. Total)		Population-weighted 2020 Annual Fire $PM_{2.5}$	
Region	Monitored	Unmonitored	Daily Mean, μg/m^3	Percent of Total $PM_{2.5}$
Midwest	44.5 (14)	24.5 (7)	0.6	7%
Northeast	45.3 (14)	12.3 (4)	0.3	4%
South	77.0 (23)	49.4 (15)	0.8	10%
West	68.6 (21)	7.9 (2)	4.6	44%
Nation	235.3 (71)	94.0 (29)	1.6	16%

For definition of abbreviations, *see* Table 1.
Monitored populations include those living in a county with an active Federal Reference Method or Federal Equivalency Method $PM_{2.5}$ monitor.
Annual fire $PM_{2.5}$ is based on county-level average concentrations and weighted by population.

Table 6. National annual health impacts from total wildland fire $PM_{2.5}$ (2019)

Health Endpoint	Impacts due to Wildland Fire $PM_{2.5}$
Mortality*	
All-cause (40)	28,000 (27,300 to 28,700)
All-cause (41)	39,700 (26,700 to 52,200)
All-cause (42)†	4,080 (242 to 7,890)
Lung cancer diagnosis	5,910 (3,080 to 8,600)
Morbidity	
Emergency room visits, respiratory	13,250 (2,680 to 26,930)
Hospital admissions, neurological	7,060 (5,310 to 8,600)
Hospital admissions, respiratory	400 (20 to 760)
New onset asthma & hay fever/rhinitis	395,560 (112,760 to 582,240)
Adversely impacted days	
Acute respiratory symptoms	14,040,000 (11,800,000 to 16,200,000)
Asthma symptoms (albuterol use)	7,310,000 (−4,330,000 to 16,100,000)
Work loss days	2,550,000 (2,190,000 to 2,880,000)
Adverse birth outcomes	
Low birth weight	2,570 (1,500 to 3,740)
Preterm birth	4,330 (2,200 to 6,730)

For definition of abbreviations, *see* Table 1.
Data in parentheses are 95% confidence intervals. All counties in the contiguous United States
9 as available in the model of Tong and coworkers (2020) were included in this analysis
(*N* = 3,107). Suppressed low counts of adverse birth outcomes resulted in a smaller subset of counties assessed for this endpoint (*n* = 573).
*Individual study results are reported for mortality impacts as a result of key differences in their methodologies.
†Wildfire-specific concentration–response function.

temporal comparisons of time periods with and without smoke exposure or satellite-based imagery of plume areas to
4 determine smoke locations (35, 48, 49). This analysis also provides additional insight into the nationwide impacts of wildland fires, not only in the western United States, where the impacts are greatest (36, 50). Overall, it is clear that the magnitude of adverse health impacts from wildland fires constitutes a serious, and likely increasing, problem for much of the United States. This is particularly true for the western and southern regions of the country, where wildland fires contribute a sizable portion of total $PM_{2.5}$.

Table 7. National annual health impacts from total wildland fire ozone (2019)

Health Endpoint	Impacts due to Wildland Fire O_3
Mortality*	
All-cause (43)	828 (295 to 1,340)
Respiratory (41)	973 (675 to 1,260)
Morbidity	
Emergency room visits, respiratory	3,180 (670 to 6,850)
Hospital admissions, respiratory	130 (−30 to 280)
New onset asthma and hay fever/rhinitis	55,260 (28,460 to 74,480)
Adversely impacted days	
Acute respiratory symptoms	941,000 (379,000 to 1,480,000)
Asthma symptoms	1,920,000 (−245,000 to 3,910,000)
School loss days	692,000 (−102,000 to 1,390,000)
Adverse birth outcomes	
Low birth weight	320 (40 to 610)
Preterm birth	90 (0 to 180)

Data in parentheses are 95% confidence intervals. All counties in the contiguous United States as available in the model of Tong and coworkers (2020) were included in this analysis (*N* = 3,106). Suppressed low counts of adverse birth outcomes resulted in a smaller subset of counties assessed for this endpoint (*n* = 573).
*Individual study results are reported for mortality impacts as a result of key differences in their methodologies.

Estimates of mortality impacts attributable to wildland fires vary widely depending on the health impact function that is selected for use in the analysis. Other studies have provided estimates of mortality impacts from wildland fires (13, 51) but have not had access to wildland fire–specific health functions. Differences in estimates may also be attributable in part to the inclusion of agricultural burning as a type of wildland fire and the year-to-year variability that can define this important emission source (38). Perhaps more important than providing quantified nationwide estimates, the present study demonstrates local estimates that show that important health impacts are occurring not just in close proximity in time and location to large individual fires, but more so as the cumulative impact of fires burning throughout the year in many locations around the country.

There is a pressing need for more wildland fire–specific health functions for use in health impact assessments. At present, there is relatively little research on the toxicity of wildland fire $PM_{2.5}$ relative to total ambient $PM_{2.5}$ from all sources (52–54). Smoke components vary widely based on fuel type, including not only various biomass sources but also manmade structures inside the expanding wildland–urban interface (55). Because most fires in the United States originate in rural areas without air quality monitoring (39), existing $PM_{2.5}$ health damage functions may be biased toward urban pollution exposures and unsuitable for smoke-specific epidemiological studies. Early evidence from observational and animal studies suggests that wildfire smoke affects respiratory health more than other $PM_{2.5}$ sources (56, 57) but is less likely to impact cardiovascular outcomes, which drive mortality impacts (58, 59). The wildland fire–specific function used in this report contains only short-term exposure impact and does not account for any increased impact occurring from prolonged, long-term exposures to $PM_{2.5}$ from wildland fires. These long-term exposures are associated with increased atherosclerotic activity (60), which may explain why the results of chronic exposures are so much greater than the sum of short-term mortalities. It is very likely that the best estimate for wildland fire $PM_{2.5}$ lies somewhere between the fire-specific function for short-term effects and the standard function for long-term exposure from more typical ambient air pollution.

Table 8. Comparison of state-level mortalities attributable to wildland fire $PM_{2.5}$ based on standard and wildland fire–specific health functions

State	Mortalities due to Wildland Fire $PM_{2.5}$	
	Standard Function*	Wildland Fire–Specific Function†
Alabama	583 (567–598)	85 (5–164)
Arizona	636 (619–653)	91 (5–177)
Arkansas	270 (263–277)	38 (2–73)
California	11,801 (11,492–12,099)	1,768 (105–3,416)
Colorado	578 (563–593)	87 (5–169)
Connecticut	64 (62–66)	9 (1–17)
Delaware	25 (24–26)	4 (0–7)
District of Columbia	12 (12–13)	2 (0–5)
Florida	958 (932–983)	131 (8–255)
Georgia	725 (706–744)	111 (7–216)
Idaho	341 (332–350)	48 (3–92)
Illinois	426 (415–438)	61 (4–118)
Indiana	237 (230–243)	34 (2–66)
Iowa	170 (165–174)	23 (1–44)
Kansas	210 (204–215)	29 (2–57)
Kentucky	197 (192–202)	29 (2–56)
Louisiana	331 (322–340)	51 (3–98)
Maine	17 (17–18)	2 (0–4)
Maryland	154 (150–158)	23 (1–44)
Massachusetts	104 (102–107)	15 (1–28)
Michigan	269 (261–276)	37 (2–72)
Minnesota	205 (200–211)	28 (2–54)
Mississippi	277 (270–284)	41 (2–80)
Missouri	389 (378–399)	55 (3–108)
Montana	175 (170–180)	23 (1–45)
Nebraska	115 (112–118)	16 (1–30)
Nevada	434 (423–445)	63 (4–122)
New Hampshire	19 (19–20)	3 (0–5)
New Jersey	219 (213–225)	30 (2–59)
New Mexico	131 (127–134)	19 (1–36)
New York	335 (326–344)	48 (3–93)
North Carolina	511 (497–525)	74 (4–143)
North Dakota	32 (31–33)	5 (0–9)
Ohio	396 (385–406)	56 (3–109)
Oklahoma	262 (255–268)	38 (2–73)
Oregon	2,196 (2,139–2,252)	298 (18–576)
Pennsylvania	400 (389–411)	54 (3–104)
Rhode Island	20 (20–21)	3 (0–5)
South Carolina	317 (308–325)	46 (3–90)
South Dakota	52 (51–53)	7 (0–14)
Tennessee	360 (350–369)	53 (3–103)
Texas	1,117 (1,087–1,146)	169 (10–328)
Utah	130 (127–134)	20 (1–40)
Vermont	9 (9–9)	1 (0–2)
Virginia	281 (273–288)	40 (2–77)
Washington	1,162 (1,131–1,192)	165 (10–320)
West Virginia	77 (75–79)	11 (1–21)
Wisconsin	195 (190–200)	26 (2–51)
Wyoming	59 (58–61)	8 (0–16)

For definition of abbreviations, *see* Table 1.
Data in parentheses are 95% confidence intervals.
*All-cause mortality from Di and coworkers (40).
†All-cause mortality in the United States from Chen and coworkers (42).

Disparity Considerations

EPA regulations require air quality monitors be sited in counties with high populations, so, on a national scale, urban areas with larger proportions of racial and ethnic minorities have greater access to monitoring data because they are populous. At smaller spatial scales, however, insufficient spatial resolution of exposure data may mask health-relevant peaks in air pollution, preventing the identification of communities experiencing environmental injustice from a local regulator's perspective (61). In this report, estimates of health impacts from air pollution exceeding the ATS recommended levels represent only counties with valid monitoring data, which is approximately one third of the total number of counties in the United States. This likely includes the majority of true health impacts in the entire United States because these counties have greater populations, but it is not informed by subcounty exposures because of the sparsity of existing ground networks. Additionally, because individual county-level results are more commonly available in urban areas (with greater populations), rural counties are left without information regarding their air pollution exposures and the resulting health impacts experienced by their occupants. Representatives from the EPA, local agencies, and stakeholders recognize the insufficiency of current monitoring networks and the need for higher spatiotemporal resolution of air quality data (62). Interviews of these individuals by the Government Accountability Office revealed a commonly expressed need for better information on air quality in rural areas, where monitor density is far lower than in urban centers, an issue that has also been emphasized by the World Health Organization (48).

Differences in underlying baseline incidences of adverse health outcomes can result in increased air pollution–related adverse health outcomes even for two locations with the same level of ambient pollution. For example, multiple studies have established differences in rates of preterm birth and low birth weight across socioeconomic groupings and race/ethnicity (49, 63), yet the relative contributions of inequalities in environmental exposures, healthcare quality or access, and other upstream determinants is unclear. Inequalities in exposures by race/ethnicity or income can result in additional air pollution–related health burdens as a result of large within-county differential exposures (64). Because this analysis is based on pollution exposures and baseline health statistics at the county level, it is unable to fully quantify the magnitude of these inequalities.

In the context of smoke exposures, disparities are highly dependent on regional population demographic characteristics and fire types. In the western United States, wildfires often originate near small, wealthy, White communities at or near the wildland–urban interface. However, large wildfire plumes can travel far. In California, smoke often settles at lower elevations, where many immigrant farmworkers live and work (65). For prescribed burns, Kondo and coworkers (50) found disproportionate smoke exposures in racial/ethnic minorities and low-income counties across the United States but no additional health burdens in these groups due to the resulting wildfire prevention (50). Generally, much more investigation is needed to fully understand the impacts of fire $PM_{2.5}$ on different 5 demographic groups (66). This research is becoming increasingly important with changing meteorological conditions related to climate change, impacting not only wildfire activity but ambient air quality as a whole while increasing the health burdens in already vulnerable communities.

Conclusions

The policy-relevant estimates of adverse health impacts associated with ambient outdoor air pollution included in this report show that there are tremendous public health benefits that are achievable through the adoption and attainment of the ATS recommended levels for $PM_{2.5}$ and O_3. Outdoor air pollution in the United States impacts every city and region, but the magnitude of these impacts is dependent on ambient pollutant concentrations, baseline health risks, and the size and age distribution of the exposed populations.

This report emphasizes the impact that air pollution has across the full life spectrum, from exposures that occur before birth to the very end of life. This includes thousands of adverse birth outcomes due to exposures starting before birth, tens of thousands of major morbidities, and millions of adversely impacted days that occur as a result of exposures continuing through childhood and adulthood, culminating in thousands of new cases of lung cancer and tens of thousands of early deaths due to exposures that occur later in life.

Although we will never fully eliminate outdoor air pollution, the large magnitude of adverse health impacts estimated in this report can be avoided through the policy framework that already exists under the Clean Air Act if more health protective standards were adopted by the EPA. The need for improved federal air quality standards is heightened by the already large, and expected-to-increase, number of adverse health impacts attributable to air pollution from wildland fires, which presents an even more difficult air quality management challenge. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

References

1 Cromar KR, Gladson LA, Ghazipura M, Ewart G. Estimated excess morbidity and mortality associated with air pollution above American Thoracic Society-recommended standards, 2013–2015. American Thoracic Society and Marron Institute report. *Ann Am Thorac Soc* 2018;15:542–551.

2 Cromar KR, Gladson LA, Ewart G. Trends in excess morbidity and mortality associated with air pollution above American Thoracic Society-recommended standards, 2008–2017. *Ann Am Thorac Soc* 2019;16:836–845.

3 Cromar KR, Gladson LA, Hicks EA, Marsh B, Ewart G. Excess morbidity and mortality associated with air pollution above American Thoracic Society recommended standards, 2017–2019. *Ann Am Thorac Soc* 2022;19:603–613.

4 Baghdikian C. Wildland Fire Research Framework 2019. Washington, DC: U.S. Environmental Protection Agency; 2019.

5 Hopke JE. Connecting extreme heat events to climate change: media coverage of heat waves and wildfires. *Environ Commun* 2020;14: 492–508.

6 Wildland Fire Leadership Council (WFLC). Joint Vision Statement on Relative Benefits of Prescribed Fire to Wildland Fire. Washington, DC: U.S. Departments of the Interior, Agriculture, Defense, and Homeland Security; 2020.

7 Burke M, Driscoll A, Heft-Neal S, Xue J, Burney J, Wara M. The changing risk and burden of wildfire in the United States. *Proc Natl Acad Sci USA* 2021;118:1–6.

8 O'Dell K, Bilsback K, Ford B, Martenies SE, Magzamen S, Fischer EV, Pierce JR. Estimated mortality and morbidity attributable to smoke plumes in the United States: not just a Western US problem. Geohealth 2021;5:e2021GH000457.

9 Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. *Proc Natl Acad Sci USA* 2016;113: 11770–11775.

10 Ellis TM, Bowman DMJS, Jain P, Flannigan MD, Williamson GJ. Global increase in wildfire risk due to climate-driven declines in fuel moisture. Glob Chang Biol 2022;28:1544–1559.

11 Kirchmeier-Young MC, Gillett NP, Zwiers FW, Cannon AJ, Anslow FS. Attribution of the influence of human-induced climate change on an extreme fire season. *Earths Futur* 2019;7:2–10.

12 Schweizer DW, Cisneros R. Forest fire policy: change conventional thinking of smoke management to prioritize long-term air quality and public health. *Air Qual Atmos Health* 2017;10:33–36.

13 Ford B, Val Martin M, Zelasky SE, Fischer EV, Anenberg SC, Heald CL, *et al.* Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. *Geohealth* 2018;2:229–247.

14 Jaffe DA, O'Neill SM, Larkin NK, Holder AL, Peterson DL, Halofsky JE, *et al.* Wildfire and prescribed burning impacts on air quality in the United States. *J Air Waste Manag Assoc* 2020;70:583–615.

15 Baker KR, Woody MC, Tonnesen GS, Hutzell W, Pye HOT, Beaver MR, *et al.* Contribution of regional-scale fire events to ozone and PM2.5 air quality estimated by photochemical modeling approaches. *Atmos Environ* 2016;140:539–554.

16 Cisneros R, Preisler HK, Schweizer D, Gharibi H. Determining the impact of wildland fires on ground level ambient ozone levels in California. *Atmosphere* 2020;11:1131.

17 Behrman RE, Butler AS, editors. Preterm birth: causes, consequences, and prevention. Washington, DC: National Academies Press; 2007.

18 de Mendonça ELSS, de Lima Macêna M, Bueno NB, de Oliveira ACM, Mello CS. Premature birth, low birth weight, small for gestational age and chronic non-communicable diseases in adult life: a systematic review with meta-analysis. *Early Hum Dev* 2020;149: 105154.

19 Schieve LA, Tian LH, Rankin K, Kogan MD, Yeargin-Allsopp M, Visser S, *et al.* Population impact of preterm birth and low birth weight on developmental disabilities in US children. *Ann Epidemiol* 2016;26: 267–274.

20 Crump C. An overview of adult health outcomes after preterm birth. *Early Hum Dev* 2020;150:105187.

21 Gibbons JTD, Wilson AC, Simpson SJ. Predicting lung health trajectories for survivors of preterm birth. *Front Pediatr* 2020;8:318.

22 Kotecha SJ, Edwards MO, Watkins WJ, Henderson AJ, Paranjothy S, Dunstan FD, *et al.* Effect of preterm birth on later FEV1: a systematic review and meta-analysis. *Thorax* 2013;68:760–766.

23 Rappazzo KM, Nichols JL, Rice RB, Luben TJ. Ozone exposure during early pregnancy and preterm birth: a systematic review and meta-analysis. *Environ Res* 2021;198:111317.

24 Li C, Yang M, Zhu Z, Sun S, Zhang Q, Cao J, *et al.* Maternal exposure to air pollution and the risk of low birth weight: a meta-analysis of cohort studies. *Environ Res* 2020;190:109970.

25 Ghosh R, Causey K, Burkart K, Wozniak S, Cohen A, Brauer M. Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories. *PLoS Med* 2021;18: e1003718.

26 Nagiah S, Phulukdaree A, Naidoo D, Ramcharan K, Naidoo RN, Moodley D, *et al.* Oxidative stress and air pollution exposure during pregnancy: a molecular assessment. *Hum Exp Toxicol* 2015;34: 838–847.

27 Cai J, Zhao Y, Liu P, Xia B, Zhu Q, Wang X, *et al.* Exposure to particulate air pollution during early pregnancy is associated with placental DNA methylation. *Sci Total Environ* 2017;607–608: 1103–1108.

28 Melody SM, Ford J, Wills K, Venn A, Johnston FH. Maternal exposure to short-to medium-term outdoor air pollution and obstetric and neonatal outcomes: a systematic review. *Environ Pollut* 2019;244: 915–925.

29 Wong EY, Gohlke J, Griffith WC, Farrow S, Faustman EM. Assessing the health benefits of air pollution reduction for children. *Environ Health Perspect* 2004;112:226–232.

30 Trasande L, Malecha P, Attina TM. Particulate matter exposure and preterm birth: estimates of U.S. attributable burden and economic costs. *Environ Health Perspect* 2016;124:1913–1918.

31 Kim JJ, Axelrad DA, Dockins C. Preterm birth and economic benefits of reduced maternal exposure to fine particulate matter. *Environ Res* 2019;170:178–186.

32 Cromar KR, Gladson LA, Perlmutt LD, Ghazipura M, Ewart GW. American Thoracic Society and Marron Institute report. Estimated excess morbidity and mortality caused by air pollution above American Thoracic Society-recommended standards, 2011-2013. *Ann Am Thorac Soc* 2016;13:1195–1201.

33 Part 50—National Primary and Secondary Ambient air Quality Standards. 40 CFR §50.

34 United States Department of Health and Human Services (US DHHS), Centers for Disease Control and Prevention (CDC), National Center for Health Statistics (NCHS). Underlying Cause of Death 1999–2020 on CDC WONDER Online Database, released 2021 [updated ■■■; accessed 2022 Nov 4]. Available from: https://wonder.cdc.gov/Deaths-by-Underlying-Cause.html. 6

35 US Environmental Protection Agency (EPA). Environmental benefits mapping and analysis program—community edition (BenMAP-CE), v. 1.5. Research Triangle Park, NC: Environmental Protection Agency; 2021.

36 United States Department of Health and Human Services (US DHHS), Centers for Disease Control and Prevention (CDC), National Center for Health Statistics (NCHS), Division of Vital Statistics. Natality public-use data 2016–2020, on CDC WONDER Online Database, 2021 [published 2021 October; accessed 2021 Nov 16]. Available from: https://wonder.cdc.gov/natality-expanded-current.html.

37 U.S. Environmental Protection Agency. Environmental benefits mapping and analysis program – community edition user's manual. Washington, DC: U.S. Environmental Protection Agency; 2023.

38 Li Y, Tong D, Ma S, Zhang X, Kondragunta S, Li F, *et al.* Dominance of wildfires impact on air quality exceedances during the 2020 record-breaking wildfire season in the United States. Geophys Res Lett 2021; 48:e2021GL094908.

39 Koman PD, Billmire M, Baker KR, de Majo R, Anderson FJ, Hoshiko S, *et al.* Mapping modeled exposure of wildland fire smoke for human health studies in California. *Atmosphere (Basel)* 2019;10:308.

40 Di Q, Wang Y, Zanobetti A, Wang Y, Koutrakis P, Choirat C, *et al.* Air pollution and mortality in the Medicare population. *N Engl J Med* 2017; 376:2513–2522.

41 Turner MC, Jerrett M, Pope CA III, Krewski D, Gapstur SM, Diver WR, *et al.* Long-Term ozone exposure and mortality in a large prospective study. *Am J Respir Crit Care Med* 2016;193:1134–1142.

42 Chen G, Guo Y, Yue X, Tong S, Gasparrini A, Bell ML, *et al.* Mortality risk attributable to wildfire-related PM$_{2.5}$ pollution: a global time series study in 749 locations. *Lancet Planet Health* 2021;5:e579–e587.

43 Katsouyanni K, Samet JM, Anderson HR, Atkinson R, Le Tertre A, Medina S, *et al.*; HEI Health Review Committee. Air pollution and health: a European and North American approach (APHENA). *Res Rep Health Eff Inst* 2009;142:5–90.

44 American Cancer Society. Lung cancer survival rates; 2022 [updated ■■■; accessed 2023 Jan 17]. Available from: https://www.cancer.org/cancer/lung-cancer/detection-diagnosis-staging/survival-rates.html. 7

45 Thurston GD, Balmes JR, Garcia E, Gilliland FD, Rice MB, Schikowski T, *et al.* Outdoor air pollution and new-onset airway disease. An official American Thoracic Society workshop report. *Ann Am Thorac Soc* 2020;17:387–398.

46 Michikawa T, Morokuma S, Yamazaki S, Takami A, Sugata S, Yoshino A, *et al.* Exposure to chemical components of fine particulate matter and ozone, and placenta-mediated pregnancy complications in Tokyo: a register-based study. *J Expo Sci Environ Epidemiol* 2022;32:135–145.

47 Sun S, Wang J, Cao W, Wu L, Tian Y, Sun F, *et al.* A nationwide study of maternal exposure to ambient ozone and term birth weight in the United States. *Environ Int* 2022;170:107554.

48 World Health Organization. WHO Global Air Quality Guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Geneva, Switzerland: World Health Organization; 2021.

49 Blumenshine P, Egerter S, Barclay CJ, Cubbin C, Braveman PA. Socioeconomic disparities in adverse birth outcomes: a systematic review. *Am J Prev Med* 2010;39:263–272.

50 Kondo MC, Reid CE, Mockrin MH, Heilman WE, Long D. Socio-demographic and health vulnerability in prescribed-burn exposed versus unexposed counties near the National Forest System. *Sci Total Environ* 2022;806:150564.

51 Fann N, Alman B, Broome RA, Morgan GG, Johnston FH, Pouliot G, *et al.* The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Sci Total Environ* 2018;610-611:802–809.

52 Dong TTT, Hinwood AL, Callan AC, Zosky G, Stock WD. In vitro assessment of the toxicity of bushfire emissions: a review. *Sci Total Environ* 2017;603-604:268–278.

53 Yong Ho K, Warren SH, Krantz QT, King C, Jaskot R, Preston WT, *et al.* Mutagenicity and lung toxicity of smoldering vs. flaming emissions from various biomass fuels: implications for health effects from wildland fires. Environ Health Perspect (Online) 2018;126:017011.

54 Liu JC, Mickley LJ, Sulprizio MP, Yue X, Peng RD, Dominici F, *et al.* Future respiratory hospital admissions from wildfire smoke under climate change in the Western US. *Environ Res Lett* 2016;11:124018.

55 Rice MB, Henderson SB, Lambert AA, Cromar KR, Hall JA, Cascio WE, *et al.* Respiratory impacts of wildland fire smoke: future challenges and policy opportunities. An Official American Thoracic Society workshop report. *Ann Am Thorac Soc* 2021;18:921–930.

56 Aguilera R, Corringham T, Gershunov A, Benmarhnia T. Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nat Commun* 2021; 12:1493.

57 Wegesser TC, Pinkerton KE, Last JA. California wildfires of 2008: coarse and fine particulate matter toxicity. *Environ Health Perspect* 2009;117: 893–897.

58 Thurston G, Awe Y, Ostro B, Sanchez-Triana E. Are all air pollution particles equal? How constituents and sources of fine air pollution particles (PM2.5) affect health. Washington, DC: World Bank; 2021.

59 Yu Y, Zou WW, Jerrett M, Meng YY. Acute health impact of convectional and wildfire-related PM2.5: a narrative review. Environ Adv 2022;12: 100179.

60 Bevan GH, Al-Kindi SG, Brook RD, Münzel T, Rajagopalan S. Ambient air pollution and atherosclerosis: insights into dose, time, and mechanisms. *Arterioscler Thromb Vasc Biol* 2021;41:628–637.

61 Paolella DA, Tessum CW, Adams PJ, Apte JS, Chambliss S, Hill J, *et al.* Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States. *Environ Sci Technol Lett* 2018;5:436–441.
62 U.S. Government Accountability Office (GAO). Opportunities to better sustain and modernize the National Air Quality Monitoring System. Publication no. GAO-21-38. Washington, DC: Government Accountability Office; 2020.
63 Braveman P, Dominguez TP, Burke W, Dolan SM, Stevenson DK, Jackson FM, *et al.* Explaining the Black-White disparity in preterm birth: a consensus statement from a multi-disciplinary scientific work group convened by the March of Dimes. *Front Reprod Health* 2021; 3:684207.
64 Clark LP, Harris MH, Apte JS, Marshall JD. National and intraurban air pollution exposure disparity estimates in the United States: impact of data-aggregation spatial scale. *Environ Sci Technol Lett* 2022;9:786–791.
65 Méndez M, Flores-Haro G, Zucker L. The (in)visible victims of disaster: understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum* 2020;116:50–62.
66 Reid CE, Maestas MM. Wildfire smoke exposure under climate change: impact on respiratory health of affected communities. *Curr Opin Pulm Med* 2019;25:179–187.

AUTHOR QUERIES

Please check all figure text, labels, and legends for accuracy and completeness.

QA1 If you provided an ORCID ID at submission, please confirm that it appears correctly on the opening page of this article.

QA2 Please confirm that all necessary grants and funding sources are mentioned in the support footnote.

1 Please provide academic/medical degree(s) (M.D., Ph.D., etc. [but not US fellowships, memberships, or honorary degrees]) for the corresponding author.

2 Tables cannot be designated with letters, so the tables have been renumbered with each having its own number. The eight tables are now numbered 1-8. Please verify the callouts are correct throughout the paper.

3 The original ref. 82, Katsouyanni 2009, was mentioned here but not cited. It is now cited as ref. 43, with subsequent references renumbered. Please verify agreement between the citations and the reference list throughout the paper.

4 Original refs. 60, 61, and 65 were cited out of order in this paragraph and have been renumbered so the citations are in numerical order, with later references also renumbered. Please verify agreement between citations and the list throughout the paper.

5 With the exception of ref. 82, which is now ref. 43, references 66-86 were not cited in the paper and have been deleted. Please ensure these references are included in the data supplement, where they are cited, because they will not appear with the published article.

6 Please provide the date on which ref. 34 was published or most recently updated before it was accessed for the preparation of this paper.

7 Please provide the date on which ref. 44 was most recently updated before it was accessed for the preparation of this paper; the date currently listed on the page is more recent than the accessed date.

8 Please confirm that all figures and tables are original to this manuscript and have not previously appeared elsewhere in any print or electronic form (including the Internet). If they have appeared elsewhere, please provide the reference of the source, as well as confirmation that written permission to reprint (or reprint with modifications) has been received (or that the original is in the public domain). If the original is an ATS publication, permission is automatically granted.

9 No reference in the list matches “Tong and coworkers (2020)” from Tables 7 and 8. Please provide a reference for this citation, add it to the end of the list, and cite it here.