Trends in Excess Morbidity and Mortality Associated with Air Pollution above American Thoracic Society–Recommended Standards, 2008–2017

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Abstract

Rationale: Air quality improvements are increasingly difficult to come by as modern pollution control technologies and measures have been widely implemented in the United States. Although there have been dramatic improvements in air quality over the last several decades, it is important to evaluate changes in the health impacts of air pollution for a more recent time period to better understand the current trajectory of air quality improvements.

Objectives: To provide county-level estimates of annual air pollution–related health outcomes across the United States and to evaluate these trends from 2008 to 2017, presented as part of the annual American Thoracic Society (ATS)/Marron Institute "Health of the Air" report.

Methods: Daily air pollution values were obtained from the U.S. Environmental Protection Agency's Air Quality System for monitors in the United States from 2008 to 2017. Concentration-response functions used in the ATS/Marron Institute "Health of the Air" report were applied to the pollution increments corresponding to differences between the rolling 3-year design values (reported as the third year) and ATS-recommended levels for annual particulate matter less than or equal to 2.5 μm in aerodynamic diameter ($PM_{2.5}$; 11 $\mu g/m^3$), short-term $PM_{2.5}$ (25 $\mu g/m^3$), and ozone (O_3; 60 ppb). Health impacts were estimated at the county level in locations with valid monitor data.

Results: Annual excess mortality in the United States due to air pollution levels greater than recommended by the ATS decreased from approximately 12,600 (95% confidence interval [CI], 5,470–21,040) in 2010 to 7,140 (95% CI, 2,290–14,040) in 2017. This improvement can be attributed almost entirely to reductions in $PM_{2.5}$-related mortality, which decreased by approximately 60% (reduced from 8,330 to 3,260 annual deaths), whereas O_3-related mortality remained largely unchanged, other than year-to-year variability, over the same time period (reduced from 4,270 to 3,880 annual deaths).

Conclusions: Improvements in health impacts attributable to ambient $PM_{2.5}$ concentrations have been observed across most regions of the United States over the last decade, although the rate of these improvements has leveled off in recent years. Despite two revisions of the National Ambient Air Quality Standards strengthening the standard for O_3 in 2008 and 2015, there has not yet been a substantial improvement in the health impacts attributable to O_3 during this time period. In many U.S. cities, an increase in the exposed population over the last decade has outpaced the improvements in ambient O_3 concentrations, resulting in a net increase in O_3-related health impacts over time.

Keywords: ozone; particulate matter; risk assessment; environmental policy

(Received in original form December 12, 2018; accepted in final form April 2, 2019)

Supported by the Marron Institute of Urban Management at New York University and the American Thoracic Society.

Author Contributions: K.R.C. oversaw and contributed significantly to all stages of the study. L.A.G. was involved in data acquisition, analysis, and interpretation, and in drafting and revising the manuscript. G.E. contributed to the study's conceptual design and manuscript revisions.

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This article has an online supplement, which is accessible from this issue's table of contents at www.atsjournals.org.

Ann Am Thorac Soc Vol ■■, No ■■, pp 1–10, ■■ 2019

DOI: 10.1513/AnnalsATS.201812-914OC
Internet address: www.atsjournals.org

Government and scientific institutions commonly state that air quality has improved dramatically in the United States since the passage of the Clean Air Act (1970) and its subsequent amendments. The U.S. Environmental Protection Agency (EPA) reports that between 1970 and 1990, Clean Air Act implementations prevented approximately 184,000 particulate matter (PM)-associated deaths, over 10 million cases of PM- and ozone (O_3)-associated respiratory and cardiovascular disease, and over 200 million lost school or work days (1). After the 1990 revisions to the Clean Air Act, the EPA found that by 2010 another nearly 165,000 mortalities, as well as millions of additional morbidities and impacted days, were prevented by reductions in fine particles (PM less than or equal to 2.5 μm in aerodynamic diameter [$PM_{2.5}$]) and O_3 concentrations across the United States (2). Published studies in the scientific literature have also concluded that reduced concentrations of $PM_{2.5}$ and O_3 in the United States since the passage of federal air quality standards have resulted in the prevention of associated mortalities and morbidities as well as significant improvements in life expectancy over the last several decades (3–5).

However, there has been much less evaluation of the changes in ambient air pollution and its associated health impacts that have occurred more recently, in particular over the last 10 years (6, 7). Many of the policy actions and regulations that have resulted in dramatic reductions in ambient pollution concentrations since the 1970 passage of the Clean Air Act and the 1990 revisions to the Act have already been fully implemented, making additional improvements in air quality increasingly difficult to come by (8, 9). Additionally, O_3, which is produced from reactions of precursor pollutants in the presence of sunlight, is predicted to increase in the United States due to rising global temperatures (10). Although it is not inevitable that there will be a slowdown in further improvements in ambient air quality, it is important to evaluate changes in the health impacts of air pollution for a more recent time period to better understand the current trajectory of air quality improvements in the United States.

The annual "Health of the Air" report is well positioned to facilitate an evaluation of the trends in air pollution and health in recent years by providing county-level estimates of annual air pollution–related health outcomes that occurred from 2008 to 2017. The systematic approach that was developed for the "Health of the Air" report allows for an in-depth understanding of local air quality impacts, allowing local policymakers and pollution managers to track progress over time. This information can serve as a valuable resource for the public, as well as for decision makers at federal and local levels, in crafting policies and implementation strategies to best address the public health impacts of ambient air pollution concentrations greater than those recommended by the American Thoracic Society (ATS).

Methods

Methods described in the most recent "Health of the Air" report were applied in this study to estimate the health impacts of air pollution levels above ATS recommendations (11, 12). This approach mimics the one used by the EPA in its regulatory review processes to estimate health impacts from $PM_{2.5}$ and O_3 in monitored counties across the nation. In addition to predicting health impacts from air pollution exceeding ATS recommendations for the most recently available data (design values for 2015–2017), this year's report incorporates an analysis of air pollution trends from the past 10 years. These methods are summarized below.

Daily O_3 and $PM_{2.5}$ measurements were obtained from the EPA Air Quality System for design value monitors for each year from 2008 to 2017. These values were used to create annual baseline and control datasets using a 24-hour metric for $PM_{2.5}$ and three separate metrics (1-h maximum, 8-h maximum, and 24-h mean) for O_3. Baseline values were equivalent to the rolling 3-year design values for each monitor. These design values correspond to the 3-year average of the annual mean concentration for $PM_{2.5}$, the 3-year average of the 24-hour 98th percentile value for $PM_{2.5}$, and the 3-year average of the fourth-highest daily 8-hour maximum O_3 concentration. Control values were based on ATS recommendations of 11 $\mu g/m^3$ for annual $PM_{2.5}$, 25 $\mu g/m^3$ for 24-hour $PM_{2.5}$, and 60 ppb for O_3 (13, 14). These cutoffs are lower than the existing National Ambient Air Quality Standards (NAAQS) of 12 $\mu g/m^3$ for annual $PM_{2.5}$, 35 $\mu g/m^3$ for 24-hour $PM_{2.5}$, and 70 ppb for O_3. The ATS-recommended levels used in this analysis are in accordance with previous ATS publications, which found that existing NAAQS were insufficient for protecting human health, and emphasized the need for more health-protective regulations (13, 15).

For each year from 2010 to 2017, baseline concentrations (corresponding to 3-year county design values) and control concentrations (corresponding to ATS recommendations) were paired by county and run through BenMAP-CE (version 1.4.14.1). Given that the design values are 3-year rolling estimates, the reported year corresponds to the third year in each grouping (i.e., pollution levels from 2008–2010 are reported in the results as 2010). Figures E1–E3 in the online supplement show design value trends for each pollutant over the last three "Health of the Air" report years (2011–2013, 2013–2015, and 2015–2017). Concentration-response relationships from epidemiological studies, based on EPA standard health functions, were used to calculate the health impacts of pollution levels above ATS recommendations for each county (*see* Table E1 for a full list of the studies used). These health impacts include mortality, major morbidity (acute myocardial infarction, chronic bronchitis, cardiovascular and respiratory hospital admissions, and asthma-related emergency department visits), and adversely impacted days (restricted activity days, work loss days, and school loss days). Additionally, excess lung cancer incidence from $PM_{2.5}$ exceeding ATS recommendations was estimated outside of BenMAP-CE using a pooled risk value derived from a separate meta-analysis (*see* Table E2) and based on 2011–2015 statistics available from the National Cancer Institute (16).

All health estimates were aggregated to the county, city, state, and national levels, and compared across years in R software (version 3.5.1). Health estimates, searchable by city or zip code, are available to the public using this report's accompanying online tool (https://healthoftheair.org).

Table 1. National annual excess health impacts, 2017

Health Endpoint	$PM_{2.5}$ (95% CI)	O_3 (95% CI)	Total (95% CI)
Mortality	3,260 (2,210 to 4,310)	3,880 (83 to 9,730)	7,140 (2,290 to 14,040)
Lung cancer incidence	640 (330 to 950)	—	640 (330 to 950)
Major morbidity	5,600 (1,800 to 9,270)	10,080 (−21,740 to 45,800)	15,680 (−19,940 to 55,070)
Impacted days	2,804,000 (2,303,000 to 3,302,000)	11,600,000 (2,816,000 to 23,467,000)	14,404,000 (5,119,000 to 26,768,000)

Definition of abbreviations: CI = confidence interval; $PM_{2.5}$ = particulate matter less than or equal to 2.5 μm in aerodynamic diameter.
Note: CIs are notably wider for O_3 due to a larger standard error in the underlying concentration-response function.

Results

Table 1 summarizes the 2017 estimated national health impacts from $PM_{2.5}$ and O_3 in excess of ATS-recommended levels.

The combined health impacts of these pollutants in 2017 is estimated to have resulted in approximately 7,140 excess mortalities (95% confidence interval [CI], 2,290–14,040), 15,680 major morbidities (95% CI, −19,940 to 55,070), and 14,404,000 adversely impacted days (95% CI, 5,119,000–26,768,000). An additional 640 excess cases of lung cancer incidence (95% CI, 330–950) were also attributed to $PM_{2.5}$ in 2017.

The air pollution–related mortality impact in the United States in 2017 for $PM_{2.5}$ was estimated at 3,260 excess deaths (95% CI, 2,210–4,310), which is similar in magnitude to the estimated 3,880 excess deaths (95% CI, 83–14,040) attributable to O_3. The geographic distribution of these estimated health impacts was more evenly spread across the United States for O_3 as compared with $PM_{2.5}$. Of the 530 counties with valid $PM_{2.5}$ design values, only 78 (15%) did not meet ATS-recommended concentrations; in contrast, 599 (83%) of the 726 counties with valid O_3 design values did not meet ATS recommendations.

It is important to note that although there are over 3,000 counties in the United States, estimates of health impacts were only made in areas with valid design values. Unmonitored counties are typically more rural and have lower population densities than monitored counties. Although lower-population counties are required to have air quality monitors if their design values measure at least 85% of NAAQS, there are undoubtedly some counties exceeding recommended levels that remain unmonitored (17). As a result, additional health impacts that would otherwise be included are not estimated in this report due to the lack of air quality monitors in all counties that exceed ATS-recommended levels.

Although the national mortality estimates for the two pollutants in 2017 were generally comparable in magnitude, $PM_{2.5}$ estimates were about two-thirds of O_3 for morbidity and one-fourth of O_3 for impacted days. Estimates for major morbidity were 5,600 (95% CI, 1,800–9,270)

Table 2. Top 25 cities with the most to gain by meeting the American Thoracic Society recommendations for $PM_{2.5}$ in 2017

$PM_{2.5}$ Rank	City	Excess Deaths	Lung Cancer Incidence	Excess Morbidities	Adversely Impacted Days
1	Los Angeles (Long Beach-Glendale), CA	877	153	1,700	853,966
2	Riverside (San Bernardino-Ontario), CA	698	125	1,211	612,701
3	Bakersfield, CA	252	46	470	228,115
4	Pittsburgh, PA	184	52	259	103,967
5	Fresno, CA	177	34	248	154,736
6	Visalia (Porterville), CA	109	17	194	95,475
7	Modesto, CA	84	17	150	68,414
8	Cleveland (Elyria), OH	71	19	90	39,384
9	Hanford (Corcoran), CA	70	11	62	74,614
10	Seattle (Bellevue-Everett), WA	66	16	109	67,615
11	Eugene, OR	66	14	74	41,559
12	Stockton (Lodi), CA	61	13	112	50,983
13	Oakland (Hayward-Berkeley), CA	59	12	105	56,262
14	Salt Lake City, UT	46	7	74	51,462
15	Detroit (Dearborn-Livonia), MI*	41	13	—	—
16	Medford, OR	42	10	46	21,793
17	Sacramento (Roseville-Arden-Arcade), CA	27	6	43	21,935
18	Merced, CA	24	5	42	24,177
19	Phoenix (Mesa-Scottsdale), AZ	23	5	41	19,336
20	San Jose (Sunnyvale-Santa Clara), CA	22	5	33	18,412
21	Grants Pass, OR	19	6	17	7,431
22	Boise City, ID	19	5	33	17,037
23	Madera, CA	17	4	149	14,884
24	Yakima, WA	14	3	23	10,812
25	Missoula, MT	13	3	19	11,034

Definition of abbreviations: $PM_{2.5}$ = particulate matter less than or equal to 2.5 μm in aerodynamic diameter
Note: rank values were determined from a sum value calculated using a 50,000 to 30,000 to 100 to 1 ratio of deaths, lung cancer incidence, morbidities, and impacted days, respectively.
*Data for morbidity and impacted days were unavailable in 2017.

Table 3. Top 25 cities with the most to gain by meeting the American Thoracic Society recommendations for O_3 in 2017

O_3 Rank	City	Excess Deaths	Excess Morbidities	Adversely Impacted Days
1	Los Angeles (Long Beach-Glendale), CA	445	1,400	1,789,926
2	Riverside (San Bernardino-Ontario), CA	242	587	865,670
3	New York (Jersey City-White Plains), NY-NJ	188	678	551,554
4	Phoenix (Mesa-Scottsdale), AZ	128	289	376,290
5	Chicago (Naperville-Arlington Heights), IL	122	388	370,280
6	Houston (The Woodlands-Sugar Land), TX	118	367	475,699
7	San Diego (Carlsbad), CA	112	250	375,179
8	Sacramento (Roseville-Arden-Arcade), CA	80	157	223,032
9	Anaheim (Santa Ana-Irvine), CA	77	165	256,444
10	Dallas (Plano-Irving), TX	76	234	290,074
11	Las Vegas (Henderson-Paradise), NV	63	128	154,425
12	Atlanta (Sandy Springs-Roswell), GA	52	161	201,985
13	Fort Worth (Arlington), TX	50	133	156,046
14	Fresno, CA	48	116	162,658
15	Warren (Troy-Farmington Hills), MI	48	115	104,954
16	Pittsburgh, PA	48	105	80,086
17	St. Louis, MO-IL	46	110	104,929
18	Denver (Aurora-Lakewood), CO	45	84	150,808
19	Cleveland (Elyria), OH	45	93	82,670
20	Philadelphia, PA	43	119	126,139
21	Bakersfield, CA	42	110	137,877
22	Oakland (Hayward-Berkeley), CA	36	101	128,872
23	Baltimore (Columbia-Towson), MD	35	124	86,696
24	Cincinnati, OH-KY-IN	35	80	89,329
25	Detroit-Dearborn-Livonia, MI	34	89	91,375

Note: rank values were determined from a sum value calculated using a 50,000 to 100 to 1 ratio of deaths, morbidities, and impacted days, respectively.

for $PM_{2.5}$ and 10,080 (95% CI, −21,740 to 45,800) for O_3; and estimates for impacted days were 2,804,000 (95% CI, 2,303,000–3,302,000) for $PM_{2.5}$ and 11,600,000 (95% CI, 2,816,000–23,467,000) for O_3.

Tables 2 and 3 show the top 25 cities (more specifically, metropolitan statistical areas and metropolitan districts) with the most to gain from meeting ATS-recommended air pollution standards for $PM_{2.5}$ and O_3. The rankings for these cities are most heavily based on mortality estimates, followed by lung cancer incidence, major morbidities, and finally impacted days (weightings for each category are described in Tables 2 and 3). The top two cities for both pollutants are Los Angeles (Long Beach-Glendale) and Riverside (San Bernardino-Ontario) in California. Together, these two cities account for 89% of the estimated air pollution–related deaths in California, and nearly a third of estimated excess deaths across the entire country. Health estimates and design values in 2017 for every U.S. county with a validated air quality monitor are shown in Table E4.

Trends in national health impacts from 2008 to 2017 (reported by the third year of each 3-year rolling average) are shown in Figure 1. Trends in annual excess mortality in the United States from air pollution levels above ATS-recommended standards show that there has been a combined reduction from $PM_{2.5}$ and O_3 of approximately 12,600 excess deaths (95% CI, 5,470–21,040) in 2010 to 7,140 excess deaths (95% CI, 2,290–14,040) in 2017. Most of this improvement is attributed to reductions in $PM_{2.5}$-related mortality (with changes in O_3-related mortality being best described as year-to-year variability). Similar trends are reported in Table E3, which shows annual mortality, major morbidity, adversely impacted days, and lung cancer incidence from 2010 to 2017 in aggregate and broken down by each pollutant.

The difference in trends for $PM_{2.5}$ and O_3 is also indicated by a comparison of cities with the highest numbers of excess deaths in 2010 and 2017, as shown in Figures 2 and 3 for $PM_{2.5}$ and O_3, respectively. Figure 2 shows that the total number of excess deaths in the top 10 ranked cities dropped substantially between these two years, with four cities (Chicago, IL; Houston, TX; New York City, NY; and Cincinnati, OH) no longer appearing in the top 10 places most impacted by $PM_{2.5}$ by 2017. Instead, four new cities (Visalia, CA; Modesto, CA; Hanford, CA; and Seattle, WA) rose in the ranks and are currently among the top 10. In contrast, the top 10 cities most impacted by O_3 remained largely similar between these two time points, with estimated deaths remaining relatively unchanged or even slightly increased for many of the cities. Tables E5 and E6 show ranks and deaths attributable to $PM_{2.5}$ and O_3, respectively, for all cities with estimates from 2010 to 2017.

Lastly, Figure 4 compares the time trends for the two study pollutants at the state level. Showing the 2-year intervals in the percentage of air pollution–related excess deaths attributable to $PM_{2.5}$ and O_3 from 2011 to 2017, these maps reveal that $PM_{2.5}$ went from contributing to excess health impacts across much of the country to only accounting for a majority of excess air pollution–related health impacts in the western (particularly the northwestern) parts of the United States. Additionally, many parts of the country now meet ATS recommendations for $PM_{2.5}$. An examination of county-level data over the entire study period reveals that the proportion of counties with valid design values that failed to meet ATS recommendations for $PM_{2.5}$ fell from 33% in 2010 to 15% in 2017, while the proportion of failing counties for O_3 went from 93% in 2010 to 83% in 2017.

Figure 1. Trends in excess mortality attributable to air pollution greater than American Thoracic Society recommendations. The American Thoracic Society currently makes recommendations for ambient air quality: 12 $\mu g/m^3$ for annual particulate matter less than or equal to 2.5 μm in aerodynamic diameter ($PM_{2.5}$), 35 $\mu g/m^3$ for short-term $PM_{2.5}$, and 60 ppb for O_3. Values are shown for the entire United States as well as California. Each data point corresponds to pollution concentrations from the 3-year rolling design values.

Discussion

Recent trends examined in this year's "Health of the Air" report indicate that the mortality impacts of air pollution above ATS-recommended levels fell by nearly half in the last decade. This improvement can be attributed almost entirely to reductions in $PM_{2.5}$-related mortality, which decreased by approximately 60% (reduced from 8,330 to 3,260 annual deaths), whereas O_3-related mortality remained largely unchanged, other than year-to-year variability, over the same time period (reduced from 4,270 to 3,880 annual deaths) as shown in Figure 1. This phenomenon is observed nationwide, particularly in those cities with the highest pollution health impacts (*see* Figures 2 and 3). However, the rate of improvement for $PM_{2.5}$ appears to have leveled off since 2014; future reports will be able to determine whether this is a temporary slowdown or it represents a true leveling off of pollution impacts in the United States.

Although the mortality impacts of air pollution levels greater than ATS recommendations are quantitatively similar in magnitude for $PM_{2.5}$ and O_3 for the years 2015–2017, morbidity and impacted days are much greater in magnitude for O_3. This is because $PM_{2.5}$ has a much higher ratio of mortality to morbidity risk than O_3 on a per-unit basis (18–21).

Figure 4 displays these trends at the state level, showing how the contributions of $PM_{2.5}$ and O_3 across the country went from being essentially geographically equal in 2011 to heavily weighted toward O_3 by 2017. The most recent estimates show excess $PM_{2.5}$ mortality impacts confined primarily to the Northwest, parts of the Rocky Mountain West, and California. Most of the rest of the country is meeting ATS-recommended levels, and therefore measurable excess $PM_{2.5}$-associated mortality has been reduced to zero. In the few places outside of the West that are still seeing impacts from $PM_{2.5}$, less than 50% of these outcomes are attributed to that pollutant.

From the summary in Figure 1 it appears that $PM_{2.5}$ reductions were far less drastic in California than across the nation as a whole. However, Figure 2 reveals that in the California cities with the highest health impacts from $PM_{2.5}$ (Los Angeles, Riverside, and Bakersfield), mortality decreased substantially in the last decade. The lack of larger improvements in $PM_{2.5}$ impacts in California may be explained by the fact that some cities throughout the state saw marked improvements in air quality, whereas others saw an increase in air pollution–related health events over time. Consequently, the vast majority of health impacts from particle pollution exceeding ATS recommendations are now concentrated in the state of California. In 2010, mortalities from $PM_{2.5}$ in California accounted for a full 43% of national $PM_{2.5}$ impacts. This grew to 78% in 2017 as $PM_{2.5}$ impacts fell throughout the rest of the country. In contrast, mortality impacts attributable to O_3 levels above ATS standards in California have stayed at approximately 30% of national O_3 impacts over the past decade. Meanwhile, O_3 is now the primary pollutant attributed to air pollution–related mortality impacts everywhere in the United States, excluding the most western states.

Although the frequency and severity of wildland fires have been observed to increase in recent years (22, 23), the emissions from these events are not responsible for the trends observed in this study. The design values used in this study excluded exceptional events with regulatory significance, including elevated pollution from wildland fires. Therefore, although the health impacts of wildland fires are an important public health issue that merits further attention, they are not included in the health impacts estimated in this study.

The national health impacts attributable to O_3 in this report have remained stubbornly high in the last 10 years despite two revisions of the NAAQS that strengthened the standard for O_3 in

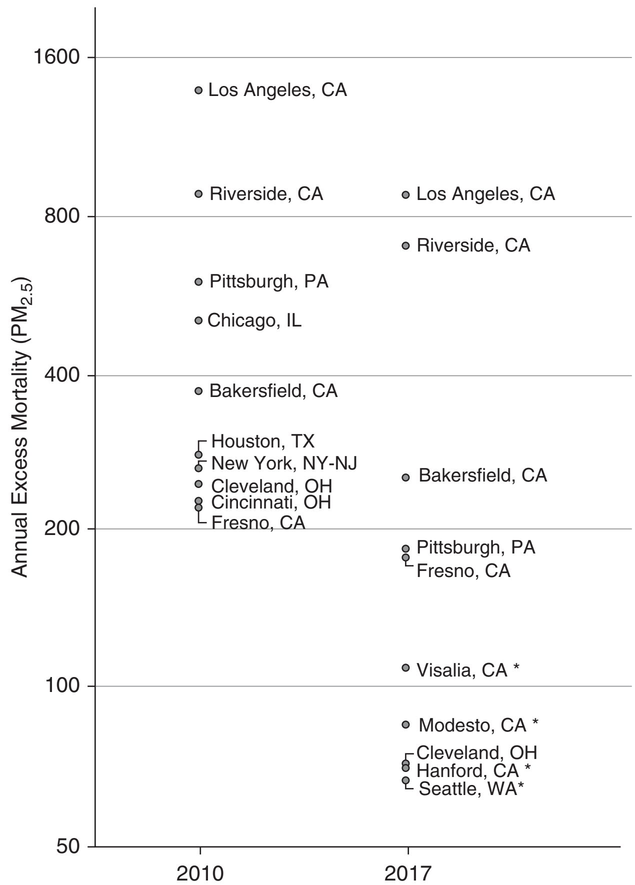

Figure 2. Excess mortality from the top 10 cities with the most to gain by meeting the American Thoracic Society recommendations for particulate matter less than or equal to 2.5 μm in aerodynamic diameter ($PM_{2.5}$), 2010 versus 2017. Values of *y*-axis follow a binary logarithmic scale. Cities in 2017 marked with an asterisk were not among the top 10 for 2010 and had mortality counts that were higher in 2017 than in previous years.

2008 and 2015 (24, 25). Given the large number of locations that currently do not meet the federal standard for O_3, much less the more stringent recommendation from the ATS, it is clear that local management of ambient O_3 will be a pressing issue over the next several years. In some locations the percentage increase in exposed populations has even grown faster than the improvements in ambient O_3 concentrations, leading to a net increase in air pollution–related health impacts. Although the total contribution of population growth to health estimates remains small (*see* Figure E4), it does highlight the need for continued improvements in air quality to even maintain the same level of health impacts.

A variety of federal and state policies have led to significant improvements in air quality in recent U.S. history. The establishment of NAAQS under the 1970 Clean Air Act amendments was the turning point for air pollution abatement measures in the United States, establishing the framework for air quality regulations still in use today. The 1970 amendments mandated the creation of State Implementation Plans to meet federal pollutant standards, jumpstarting new research in air quality and experimentation in a number of pollution reduction programs. These regulations were revised and improved over the decades with advances in air quality science and technology alongside consistent monitoring and assessment of programs. Another breakthrough came with the 1990 Clean Air Act amendments, which encouraged the use of market-based measures to meet NAAQS. The resulting multistate cap-and-trade programs used to meet federal standards may be the greatest contributors to pollution reductions in U.S. history (9). This included the Acid Rain Program, which set a cap on SO_2 emissions from electricity-generating units in the United States and permitted the buying and selling of emission allowances. The resulting health benefits in the first two decades of Acid Rain Program implementation have been estimated at $50 billion (26).

More recently, reductions in air pollution have come from a number of technology conversions. One significant conversion has been the transition from coal-fired power to natural gas energy production. With recent improvements in technology, natural gas now outpaces coal in energy efficiency, lowering its cost and resulting in natural gas being the primary source of electricity in the United States (27, 28). These improvements in energy efficiency have led to the retirement of a number of high-polluting power plants across the United States in the last decade. Nearly all of these now-closed plants were powered by fossil fuels; specifically, from 2008 to 2017, national coal capacity decreased by 17%, in addition to the shutdown of a significant number of older natural gas plants (29). These closures have also been a result of requirements laid out by the EPA's Mercury and Air Toxics Standards, and power plant retirements are projected to increase through 2020 (30).

Other technology conversions have occurred among mobile sources. The implementation of Tier II standards in 2000, regulating tailpipe emissions in all passenger vehicles and limiting fuel sulfur content, have led to dramatic improvements in air quality and emission technology. Updates to these standards in the 2017 Tier III requirements are anticipated to provide even greater reductions of a number of air pollutants while preventing thousands of excess health impacts (31). Additionally, cleaner diesel fuel and truck rules were announced in 2000 (32) and implemented over the following decade. These included a 2004 rule regulating heavy diesel equipment (33), a 2008 rule for diesel locomotives and marine vessels (34), and the development of an international program to clean up oceangoing vessels (35).

All of these programs initially led to further reductions in particle pollution, supported by data from ground monitors

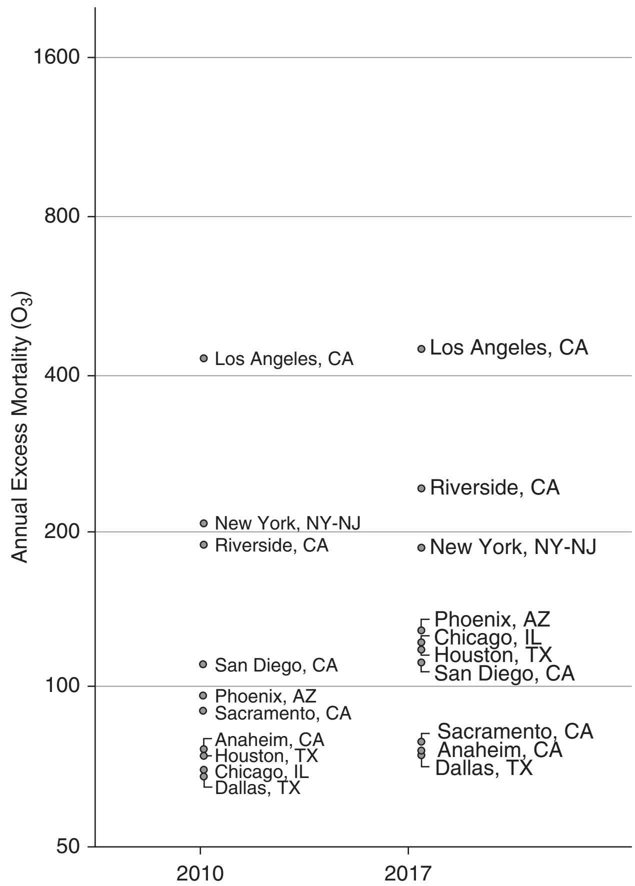

Figure 3. Excess mortality from the top 10 cities with the most to gain by meeting the American Thoracic Society recommendations for O_3, 2010 versus 2017. Values of *y*-axis follow a binary logarithmic scale.

and satellite instruments. Studies of long-term trends for particle pollution in the United States have shown dramatic reductions since the 1980s (36, 37), and other studies have shown dramatic reductions in $PM_{2.5}$ in major U.S. cities since the early 21st century (38, 39). These reductions have been the most dramatic in key industrial regions in both the eastern and western United States, and include decreases in a number of $PM_{2.5}$ precursors, such as NO_2 and SO_2 (40–42). Findings from the present study support these results, with $PM_{2.5}$ reductions occurring from 2010 to 2014. However, these improvements leveled off in most recent years as federal rules became more fully implemented and pollution concentration targets were met.

Additional improvements in both $PM_{2.5}$ and O_3 emissions may be jeopardized by changing regulatory priorities at the EPA. Under the Trump administration, the EPA has proposed to roll back or weaken several EPA policies that have both direct and indirect impacts on $PM_{2.5}$ emissions (43). Of great significance is the recent repeal of the Clean Power Plan, which would have implemented federal requirements for the energy-generating sector to reduce carbon dioxide emissions. These measures are being replaced by the Affordable Clean Energy Rule, which will significantly relax energy sector requirements (44). Data from the EPA itself predict that this repeal will result in hundreds of deaths and thousands of morbidities that would have been prevented under the Clean Power Plan (45).

Additional efforts are being made by the current administration to freeze the Corporate Average Fuel Economy standards and replace them with a Safer Affordable Fuel-Efficient vehicular rule, weakening existing fuel efficiency standards (46, 47). Other moves to deregulate air pollution abatement include a delayed implementation of the 2015 ozone standard (48), a potential revision of the Mercury Air Toxics rule (49), and several bills passed by Congress that would weaken the EPA's authority to regulate air pollution, including O_3 and $PM_{2.5}$ (50, 51). With such government actions in direct opposition to the goals of existing air quality regulations, it is not a given that past trends toward improving air quality will inevitably continue in the future.

The present report is one of a number of studies assessing the health impacts of air pollution in recent years. Although these types of health impact assessments are continuously performed for regions of the United States (52–55), a considerable number of these studies have examined the increasing health impacts from air pollution in China (56–60), as well as a number of other global cities and regions (61–66). These studies assessed a range of air quality scenarios based on national and international air quality standards, source-specific impacts, and various researcher-determined levels. Like the present study, they often relied on ground-based monitor measurements, although as satellite data are becoming increasingly refined, more and more studies are relying on these measurements to estimate health impacts. Other studies used chemical transport models based on atmospheric chemistry to make air pollution estimates used in health assessments. A number of recent studies have also taken advantage of the EPA's BenMAP software and evaluated concentration-response functions to estimate local air pollution–associated health impacts (52, 53, 66). However, the "Health of the Air" report is uniquely useful in its county-specific diagnoses provided for all monitored locations across the continental United States. Because this report is updated each year, local environmental managers and policymakers can use "Health of the Air" data to more accurately track local air quality improvements and make decisions based on uniform, up-to-date estimates.

Finally, it is important to emphasize that the annual "Health of the Air" report only presents the health impacts of pollution levels above ATS-recommended levels. These numbers do not reflect the health impacts that have been observed at levels below current ATS recommendations. For

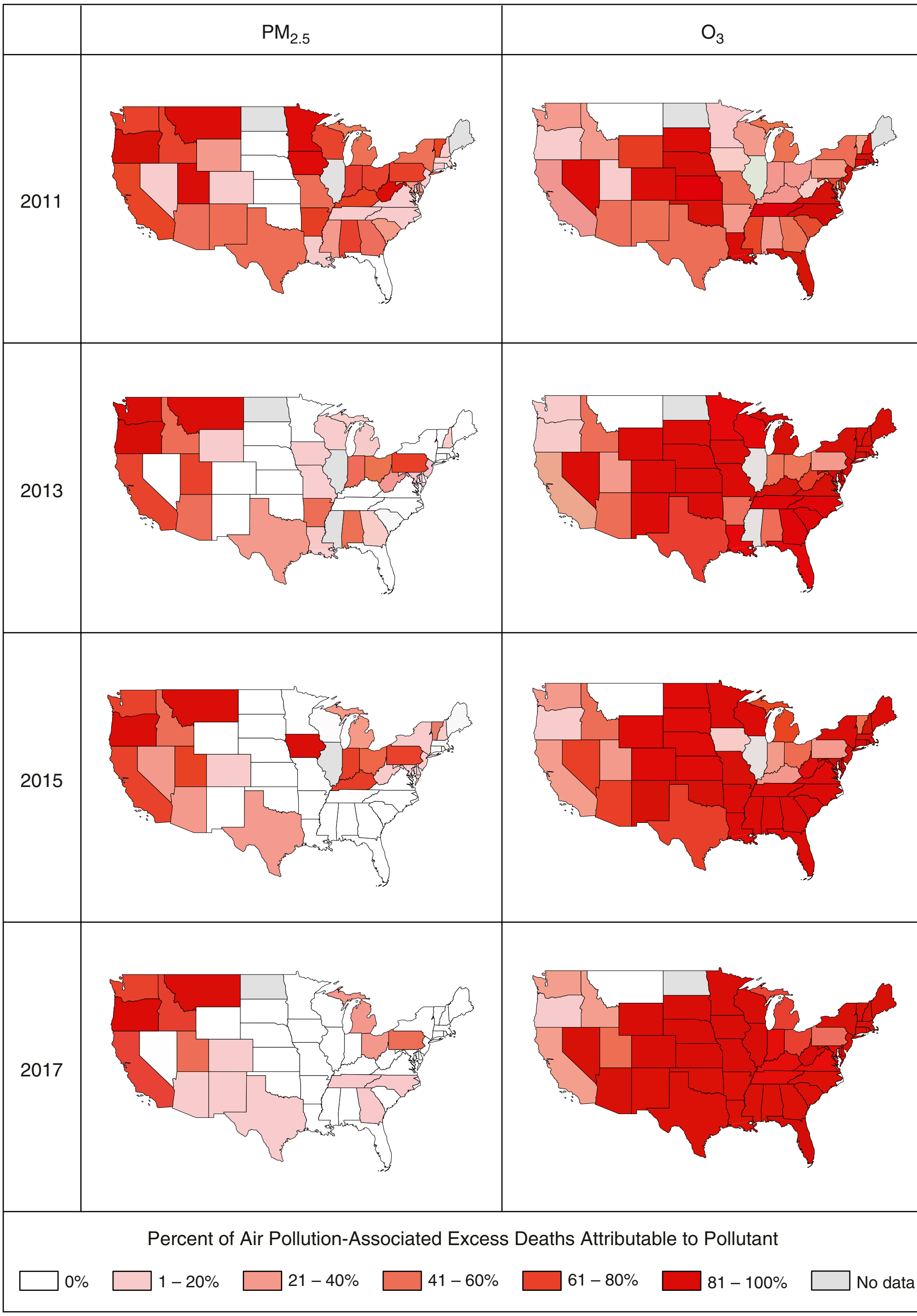

Figure 4. Percentage of air pollution–related excess deaths attributable to $PM_{2.5}$ and O_3, 2011–2017. The percentages are mutually exclusive and sum to a total of 100% for each state. States with a 0% contribution for a pollutant are already meeting American Thoracic Society–recommended levels. Some states did not have validated design values for certain years, as indicated by the gray color on the maps.

instance, significant mortality impacts have been observed from $PM_{2.5}$ and O_3 concentrations well below the existing national standards (67–69), and long-term O_3 mortality effects have been observed (70) but are not yet incorporated into legal standards or the present report. As such, even those counties that meet current ATS recommendations can expect to see further health benefits as they continue to make targeted efforts to improve local air quality.

Conclusions

Improvements in health impacts attributable to ambient $PM_{2.5}$ concentrations have been observed across most regions of the United States over the last decade, whereas O_3 impacts have remained relatively unchanged. Even maintaining current pollution levels will ultimately result in increasing numbers of mortalities and other health impacts as populations grow over time. As state and city leaders determine which policy decisions are best suited for reducing air pollution and keeping up with population growth, they can use "Health of the Air" data to target areas and design policies to best address the particular pollutants that are causing the greatest health impacts in their locales. ■

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

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