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Wildfires and the changing landscape of air pollution-related health burden in California

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Abstract

Rationale: Wildfires are a growing source of fine particulate ($PM_{2.5}$) pollution, but associated trends in health burden are not well characterized.

Objectives: We investigated trends and disparities in $PM_{2.5}$-related cardiorespiratory health burden (asthma, chronic obstructive pulmonary disease, and all-cause respiratory and cardiovascular emergency department (ED) visits and hospital admissions) for all days and wildfire smoke-impacted days across California, 2008–2016.

Methods: Using residential ZIP code and daily $PM_{2.5}$ exposures, we estimated overall- and subgroup-specific (age, gender, race/ethnicity) associations with cardiorespiratory outcomes. Health burden trends and disparities were evaluated based on relative risk, attributable number, and attributable fraction by demographic and geographic factors and over time.

Measurements and Main Results: $PM_{2.5}$-attributed burden steadily decreased, whereas the fraction attributed to wildfire smoke varied by fire season intensity, comprising up to 15% of the annual $PM_{2.5}$-burden. The highest relative risk and $PM_{2.5}$-attributed burden (92 per 100,000 people) was observed for respiratory ED visits, accounting for 2.2% of the respiratory annual

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burden. Disparities in overall morbidity in the oldest age, Black, and "Other" race groups were also reflected in $PM_{2.5}$-attributed burden, whereas Asian populations had the highest risk rate in respiratory outcomes and thus the largest fraction of the total burden attributed to the exposure. In contrast, high wildfire $PM_{2.5}$-attributed burden rates in rural, central, and northern California populations occurred due to differential exposure.

Conclusions: In California, wildfires' impact on air quality offset the public health gains achieved through reductions in non-smoke $PM_{2.5}$. Disproportionate effects could be attributed to differences in subpopulation susceptibility, relative risk, and differential exposure.

Introduction

The state of California has seen multiple mega-fires in recent years, resulting in devastating harm to property, life, and the economy.[1] In the year 2020 alone, over 9,600 fires burned, resulting in billions of dollars in economic losses.[2] In addition to the economic and social toll, wildland fires have been estimated to account for 32−44% of fine particulate matter ($PM_{2.5}$) emissions, representing the single largest source of particle pollution in the United States.[3]

Within a complex mixture of particulate and gaseous pollutants found in smoke, $PM_{2.5}$ is a primary public health concern due to its known health risks, high concentrations, and extensive dispersion during wildfires. $PM_{2.5}$ is a respiratory irritant and is causally associated with cardiovascular disease.[4] Previous studies have observed disparities in $PM_{2.5}$ exposure and associated health risks, with disproportionately higher impacts on socioeconomically disadvantaged communities[5] and communities of color.[6] Additionally, certain demographic groups, including children, the elderly, and those with chronic health conditions, are also more vulnerable to $PM_{2.5}$ health impacts, leading to higher rates of $PM_{2.5}$-related health burden.[7,8] A growing body of evidence suggests similar disparities for wildfire-$PM_{2.5}$ health effects; however, trends in wildfire smoke exposure in the population and health burden are not well-understood.[9–23]

While the frequency of wildfires has been on the rise, measurable reductions in particle pollution have been achieved in recent decades.[3] Gains in air quality have furthermore translated into improvements in health impacts from air pollution. A United States study of mortality trends showed that overall declines in $PM_{2.5}$ accounted for 5.7% of the total decline in cardiovascular mortality, but noted that $PM_{2.5}$-attributed mortality increased primarily in the areas with significant wildfire activity.[24] These current trends in wildfire activity may be changing the landscape of $PM_{2.5}$ exposure, with implications for related health burdens and disparities across sensitive populations.[25]

This manuscript characterizes recent trends in $PM_{2.5}$-related cardiorespiratory health burden experienced during wildfires in California. Daily records of emergency department visits and hospital admissions were used to derive California-specific health risk estimates by age, race/ethnicity, and gender. Health burden trends and disparities were evaluated based on relative risk, attributable number, and attributable fraction by demographic and geographic characteristics and over time. Some of the results of this study have been previously reported in the form of an talk at the 2022 Smoke Management in the Northwest Conference.

Methods

Cardiorespiratory-related emergency department (ED) visits and hospital admissions (HAs) data were acquired from the California Department of Health Care Access and Information (HCAI) for January 1, 2008 through December 31, 2016. International Classification of Diseases 9th revision and 10th revision Clinical Modification (ICD-9-CM and ICD-10-CM) diagnosis codes were used to identify ED visits and HAs related to four categories of cardiorespiratory morbidity: asthma, chronic obstructive pulmonary disease (COPD), respiratory disease (asthma, COPD, and other conditions); and cardiovascular disease (myocardial infarction, hypertension, and other conditions) (Supplementary Material (SM) Table S1). We excluded scheduled and non-acute HAs.

Visit-level information was aggregated by date and patient's residential zone improvement plan (ZIP) code ("ZIP-days"). All ZIP codes with a 2010 census population of at least 1,500 were included. Daily ZIP code-level counts of each outcome were also constructed for demographic subgroups by age (0–4, 5–18, 19–64, or 65+ for asthma and respiratory; 19–44, 45–64, or 65+ for COPD and CVD), gender (male or female), race/ethnicity (non-Hispanic White ("White"), non-Hispanic Black ("Black"), Hispanic, non-Hispanic Asian ("Asian"), non-Hispanic Native American/Aleut ("Native American"), or non-Hispanic other race ("Other," which includes individuals identifying as multiracial or with any race categorization not in HCAI).

Residential ZIP code was also used to classify ED visits and HAs by geographic characteristics. Urbanicity, defined by rural-urban commuting area (RUCA) codes, was assigned to ZIP codes based on U.S. Department of Agriculture classifications, namely "urban" (RUCA<4) or "rural" (RUCA≥4).[26] Long-term $PM_{2.5}$ concentrations not related to wildfire smoke (hereafter, "long-term air quality") were also assigned as the average daily concentrations of $PM_{2.5}$ on days identified as not impacted by wildfire smoke and aggregated to annual averages, classified as above or below 12 $\mu g/m^3$ (<12 $\mu g/m^3$ or 12+ $\mu g/m^3$) because the 12 $\mu g/m^3$ threshold corresponds to the annual National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$. Statewide reference data on race/ethnicity, gender, and age were obtained from the 2010 California Department of Finance's Demographic Research Unit.[27]

The exposure of interest was daily (24-hour mean) concentrations of ambient $PM_{2.5}$ ($\mu g/m^3$) on all days and on days impacted by wildfire smoke, obtained from a previously developed air quality model.[28,29] Briefly, aerosol optical depth (AOD) measurements were used to predict $PM_{2.5}$ concentrations on a 1 x 1 km grid using mixed effects models accounting for the time-varying relationship between $PM_{2.5}$ and AOD. Estimated concentrations exhibited strong correlation with the ground monitor measurements (R2=0.92). Gridded estimates were aggregated to census tract averages, and these were further aggregated to residential population-weighted ZIP code averages.

We utilized the intersection of smoke plume polygons from National Oceanic and Atmospheric Administration Hazard Mapping System (HMS) Fire and Smoke Product and spatial polygons to classify ZIP-days as smoke-affected days. HMS utilizes polar and geostationary satellite observations to perform automated fire detections. Structural fires, gas flaring, and other non-wildland sources of atmospheric aerosols are identified and excluded, and smoke analysts visually examine imagery data to identify false positive and false negative detections.

Daily counts of events for each outcome and demographic subgroup were modeled using Poisson regression to estimate the relative risk associated with daily $PM_{2.5}$ exposure. Relative risk estimates were not estimated by geographic characteristics or time. Each outcome model included a random intercept for ZIP code and adjustment for *a priori* selected time-varying confounders, including seasonal/long-term trends, heat index (a summary measure of temperature and humidity), and day-of-the-week. Distributed lag models were used to estimate relative risks cumulated up to seven days following each day of exposure for each outcome and demographic subgroup separately. The best-fit model with respect to parameterizations for the independent variables and the length of the lag period (same-day only (lag 0), up to seven days (lag 0–6)) for each outcome was selected based on the lowest Bayesian Information Criterion. Change in cumulative relative risk ($\mathrm{cRR_L}$) over the lag period (L) for the best-fit model was expressed as a percent change in risk per change (Δ) in $PM_{2.5}$ as $(\mathrm{cRR} - 1) \times 100\%$, where $\mathrm{cRR} = \exp\left(\Delta PM * \sum_{l=0}^{L} \beta_l\right)$ with confidence intervals corresponding to $\exp\left(\Delta PM * \left(\sum_{l=0}^{L} \beta_l \pm 1.96\ SD_{\sum_{l=0}^{L} \beta_l}\right)\right)$.

Finally, using the best fit model for each outcome, we calculated the $PM_{2.5}$-attributed health burden in absolute terms as $PM_{2.5}$-attributable number ($PM_{2.5}$-AN per 100,000 persons), and in relative terms as the Attributable Fraction ($PM_{2.5}$-AF, %) for all days and for smoke days. $PM_{2.5}$-AN of events for each day and each ZIP-code was aggregated by geographic (urbanicity, long term air quality), demographic (age, race/ethnicity, gender) characteristics, annually, for smoke days and on all other days. To do this, we first estimated the baseline population incidence for each outcome (Y_0) as an expected number of events assuming no $PM_{2.5}$ exposure. Second, AN of ED visits and HAs was calculated as a product: $Y_0 \times \left(\exp\left(\Delta PM * \sum_{l=0}^{L} \beta_l\right) - 1\right)$ for each ZIP-day and aggregated by demographic characteristics, geographic factors, or years. To calculate the $PM_{2.5}$-AN specific to the days affected by wildland fire, we repeated this process aggregating the burden over the smoke days only. Hereafter, references to "smoke-$PM_{2.5}$ burden" indicate burden attributable to $PM_{2.5}$ on smoke days (SM Appendix 1).

To obtain statewide $PM_{2.5}$-AN burden rates per 100,000 persons, we added ZIP-code ANs and divided by the 2010 California population size, and multiplied by 100,000. To obtain the $PM_{2.5}$-AN burden rates for each demographic subpopulation, we calculated the group-specific annual burden for each ZIP code, added these, and then divided this value by the estimated subgroup population size. To obtain the burden rate by geographic characteristics, we added the overall burden rates across zip codes with the same geographic characteristics and divided by the corresponding population. For brevity, the main text focuses on ED visits, with HA results presented in the SM.

Results

Across 1,297 ZIP codes, encompassing 98.1% of the 2010 California population, the annual average $PM_{2.5}$ concentration on days that were not affected by wildfire smoke ranged from 2.52 to 17 μg/m^3, with the highest concentrations observed in the Central Valley and inland area of urban Los Angeles (Figure 1A). The highest smoke exposure was observed on 5.5% of ZIP-days, most frequently in 2008 (10.0%) and in 2016 (9.9%), and in the northern and central areas and southeastern tip of the state (Figure 1B). Central California was affected by both large numbers of smoke days as well as the highest levels of $PM_{2.5}$ on non-smoke days.

The overall burden rates by demographic and geographic characteristics were not proportional to their representation in the California population (Table 1 for ED, Table S2 for HA rates). For asthma, the youngest age group (0–4) accounted for 6.8% of the population but 9.7% of ED visits with 2,151 visits per 100,000 children annually. Similarly, the oldest age group (65+) accounted for 11.4% of population, but 55.8% of COPD visits and 45.8% of CVD visits. Higher overall annual burden rates, in comparison to the population fraction, were notable across subgroups, particularly Black, Other, female, rural, and high pollution areas.

$PM_{2.5}$ exposures were associated with a statistically significant increase in risk of ED visits and HAs for all four outcomes (Figure 2). The strongest associations were observed for respiratory-related ED visits (2.27% increase in risk (95% confidence interval (CI): 2.14, 2.39) per 10 μg/m^3 increase in $PM_{2.5}$; lag 0–4) and for asthma visits (2.22% increase in risk (95% CI: 2.04, 2.40); lag 0–2) . These were followed by COPD (1.39% increase in risk (95% CI: 1.08, 1.07); lag 0–1) and CVD visits (0.89% increase in risk (95% CI: 0.80, 0.98); lag 0) . Differences in relative risk from $PM_{2.5}$ were observed between ED visits and HAs: for asthma and respiratory outcomes, the percent increase in $PM_{2.5}$-related risk of ED visits was greater than that of HAs, while for COPD and CVD, the percent increase was nearly the same.

The risk of asthma and respiratory ED visits associated with $PM_{2.5}$ exposure was highest among 65+, Asian, and Other race groups. In contrast, the risk estimates for COPD and CVD were similar in magnitude and varied little across demographic groups (Figure 2B), with the exception of Native Americans whose risks were notably higher in comparison to other race groups. However, wide confidence intervals reflected a high level of uncertainty related to the group's smaller population.

The largest $PM_{2.5}$-AN rates and AFs were observed for respiratory outcomes, with 92 ED visits per 100,000 persons annually, accounting for 2.2% of the total respiratory burden of 302,262 visits (Table 2; Table S3 for HA rates). Additionally, $PM_{2.5}$ accounted for 2.2% of the total asthma burden (107,493 visits), 1.3% of the COPD burden (19,620 visits), and 0.9% of the CVD burden (129,908 visits). Annually, the largest smoke AF was observed in 2008, accounting for 2.6% of Asthma, 1.6% of COPD, 2.7% of Respiratory, and 1.1% of CVD-related outcomes (Tables S4-S7; for HAs, Tables S8-S11). Differential $PM_{2.5}$-AN rates were largely consistent with differences in total morbidity reported in Table 1. Generally, the highest total visit rates were observed in the oldest age group (65+), Black, Native American, and Other race populations, and females. The highest rates among all the outcomes and subgroups were found for asthma-related ED visits among the Black population with a rate of 133 in comparison to 28 per 100,000 in the White population. The largest disparity of PM-attributed health burden in relative terms was observed in the Asian population, for whom $PM_{2.5}$ accounted for 3.3% of asthma and 3.2% of respiratory ED visits.

The $PM_{2.5}$-AN rate decreased over time in tandem with a decrease in $PM_{2.5}$ concentrations of 0.31±.01 μg/m^3 per year (Figure 3A). In contrast, the contribution of smoke days to the $PM_{2.5}$ health burden varied from year to year with the highest contributions observed in 2008 and 2016 (Figure 3B). Figures S1A and S1B present trends in HA burden. On average, asthma, COPD, respiratory, and CVD smoke-$PM_{2.5}$ AN rates accounted for 5.7%, 6.9%, 5.8%, and 6.2% of the $PM_{2.5}$-AN , respectively (Tables S4-S7; for HAs, Tables S8-S11). The highest wildfire smoke impact occurred in 2008, when wildfire smoke contributed 13.67%, 16.86%, 13.96%, and 15.07% of $PM_{2.5}$ related burden for asthma, COPD, respiratory, and CVD, respectively.

The magnitude of the disparities across age and race groups in $PM_{2.5}$-attributed health burden on smoke days (Table 3; Table S12 for HA rates) was generally smaller than the differences seen in their total morbidity rates (Table 1) or in $PM_{2.5}$-attributed burden rates (Table 2). Consistent with the total $PM_{2.5}$ burden rates (Table 2), the oldest age group had the largest smoke-$PM_{2.5}$ asthma burden, comprising 0.18% of the total visit rate (Table 3) or 6% of the $PM_{2.5}$ burden rate of 3.0 (Table 2). The Asian population had the highest AF for asthma and respiratory-related ED visits for smoke days (0.16% and 0.17% of total visit rate, respectively). The Native American population experienced the highest COPD and CVD smoke-$PM_{2.5}$ AFs (0.35% and 0.10% of total visits, respectively). In contrast to what was observed for the overall PM2.5 burden, the magnitude of the disparities for smoke-related burden was more pronounced across geographic factors. More specifically, rural areas had consistently higher smoke-$PM_{2.5}$ burden rates in comparison to the urban areas. Spatially, similar distributions of the burden were observed across outcomes: the central and northern parts of California experienced the greatest smoke-$PM_{2.5}$ health burden compared to coastal and southern areas, except for the southeast corner of the state (Figure 4; Figure S2 for HAs).

Discussion

We evaluated the burden of cardiorespiratory emergency department visits and hospital admissions in California attributable to $PM_{2.5}$ on all days and on days when air quality was affected by wildfire smoke, from 2008–2016. Exposure to $PM_{2.5}$ on all days accounted for between 0.9% and 2.2% of the total burden depending on the outcome, with the highest rates observed for respiratory disease. Over the study period, $PM_{2.5}$-attributed health burden steadily decreased with declining $PM_{2.5}$ concentrations, whereas the fraction of the $PM_{2.5}$ burden attributed to days with wildfire smoke varied substantially across years. In years with high fire activity, smoke days accounted for a significant proportion of the total $PM_{2.5}$ health burden: up to 15% of the $PM_{2.5}$-burden in 2008 was attributable to smoke days, suggesting wildfire-related $PM_{2.5}$ can offset the expected gains in averted cardiorespiratory events associated with reduction in non-smoke $PM_{2.5}$.

We investigated $PM_{2.5}$- and wildfire smoke-attributed health burden for each demographic group, over time, and by geographic factors using estimated relative risk estimates for both ED visits and HAs. Differences in total ambient $PM_{2.5}$-attributed health burden rates between demographic groups reflected differences in their total morbidity rates, $PM_{2.5}$-associated risk rates, and exposure levels. Total morbidity was highest among the oldest age group, Black, Native American, Other race, and rural populations. These disparities were reflected in $PM_{2.5}$-attributed health burden estimates.

The largest disparity in Respiratory burden related to $PM_{2.5}$ exposure as a fraction of total burden was observed in the Asian population which had one of the lowest total visit rates, but high $PM_{2.5}$ relative risk compared to other race groups. This may reflect their geographic distribution in California, e.g., the higher proportion of Asian populations concentrated in areas of greater air pollution such as parts of the Central Valley, and San Francisco and Los Angeles urban areas. The Other race population also experienced elevated $PM_{2.5}$ AFs for all outcomes compared to the other race groups, but it is unclear how to interpret this finding given this group's heterogeneity, as it is composed of multi-racial individuals and those who do not identify with HCAI's race/ethnicity taxonomy options.

When considering $PM_{2.5}$ burden on days affected by wildfire smoke, Asian and Other race populations, rural areas, and areas with worse long-term air quality (12+ $\mu g/m^3$) all had disproportionately elevated burden rates. Hispanics did not appear to have disproportionately high burden rates, which may be due to the younger population structure of Latinos compared to non-Latinos in California.[30] However, these results may reflect an underrepresentation of Hispanics for several reasons. Misclassification may exist: hospitals report a lesser proportion of Hispanic and a greater proportion of White patients compared to their catchment area populations.[31] Underrepresentation may also arise from the high proportion of Hispanics (92%) in the California farmworker population, which is a transient population as well as an outdoor workforce with higher exposures to air pollution.[32] Also, some research suggests lack of emergency department utilization among Hispanics with low acculturation.[33] The central portion of the state, which includes the Central Valley, experienced both greater non-smoke-$PM_{2.5}$ and smoke-$PM_{2.5}$ burden in comparison to the rest of the state. Our findings suggest the disproportionate burden of environmental risk factors and disease experienced by certain populations is conserved with regard to wildfire smoke-related cardiorespiratory burden.

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Asthma, COPD, respiratory, and cardiovascular diseases are the four main cardiorespiratory-related outcomes studied in the context of wildfire smoke.[9] The estimated relative risks were slightly smaller in magnitude compared to those referenced [13,34] in published risk assessments[35,36] of cardiorespiratory health burden from wildland fire-associated $PM_{2.5}$. The $PM_{2.5}$-associated risk for asthma and respiratory disease was substantially greater for ED visits than HAs, reflecting the more acute but transient nature of injury for some respiratory outcomes, and thus the smaller proportion of ED visits that resulted in hospitalization. We also observed greater $PM_{2.5}$ risk estimates for asthma and respiratory outcomes compared to cardiovascular outcomes, with a significant variation in risk across demographic groups. Similar results have been reported previously.[13,14,22,37] In contrast, risk estimates for COPD and CVD were similar in magnitude between ED visits and HAs. Those visiting the ED due to cardiovascular disease or COPD are more likely to require hospital admission, given the pathophysiology of the disease and the health vulnerability of the older populations that tend to be affected by these conditions.

Previously, health impacts of wildfire smoke have been estimated based on health impact assessments which rely on extrapolated concentration–response functions from epidemiological studies to estimate the number of excess health outcomes attributable to wildfire smoke exposure.[36,38–41] Cleland and colleagues (2019)[42] found that the choice of $PM_{2.5}$ health risk function is one of the biggest contributors to variability in health burden estimates. In this study, we use California-specific health risk estimates to calculate health burden at a fine spatial resolution reflecting the distribution of factors that might modify the effects of $PM_{2.5}$, such as age and socioeconomic status.[43]

This study has strengths and limitations. We leveraged modeled estimates of $PM_{2.5}$ at fine spatial resolution based on satellite measurements with high correlations to federal monitoring data.[28,29] Additionally, our analysis spanned nine years, allowing us to understand the trajectory of smoke-related health burden over time, particularly in the context of changing ambient $PM_{2.5}$ concentrations. However, as in all air pollution epidemiology, unmeasured confounding may have biased the relative risk estimates and thus biased the burden estimates. In this analysis, we also assumed that $PM_{2.5}$ toxicity does not differ substantially between ambient sources and biomass burning. This assumption is consistent with the most recent review of scientific evidence.[4] The high contribution of wildfires to total PM (up to 44%)[3] and high frequency of fires also suggest that emissions linger for extended period and account for a large portion of total mass, making it very difficult to discern the differential toxicity between ambient- and biomass-sourced PM in population studies. However, we also acknowledge that gaseous pollutants may add to health impacts during fire episodes. Specifying gaseous exposures at the population level may be important for future studies to capture the full health burden of wildfire smoke.

Satellite-based smoke detections do not always represent smoke at the ground-level, potentially over-attributing $PM_{2.5}$ burden to smoke. Since the satellite data does not capture vertical atmospheric profile, smoke plumes may reflect ground-level experiences near fires more accurately than in areas further downwind. For this reason, we used the HMS smoke plumes only to identify days affected by smoke, but use $PM_{2.5}$ concentrations as the exposure metric.

The lack of a common exposure metric has been noted as an important limitation in evaluating the relative toxicity of wildfire smoke in relation to PM from other sources, and efforts have been made calling attention to this gap.[10,44] Epidemiologic studies have examined the effect of wildfire smoke by analytically separating anthropogenic PM from wildfire [45–47] either through use of atmospheric models or by subtracting out a concentration historically observed, while others have separated PM on smoke days and non-smoke days.[13,48] We adopted the latter approach, reasoning that people breathe in the entire mixture of air and that both ambient PM and wildfire smoke contribute to the total potency of the mixture.

Wildfire smoke poses a growing threat as a source of air pollution, and many states, including California, are responding to this challenge by seeking ways to increase resilience and protect public health. An important step in this process is to understand how air pollution- and smoke-related health burden has evolved over time and identify populations at increased risk of adverse health consequences due to heightened health susceptibility and increased smoke exposure. Consideration of wildfire smoke is integral for air quality improvements in California to translate into equitable improvements in public health.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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At a Glance Commentary

Scientific Knowledge on the Subject

Acute cardiorespiratory morbidity is a sensitive health endpoint for exposure to fine particulate matter (PM2.5), a major constituent of wildfire smoke. Large wildfires have increased in frequency and in intensity. Previous studies have focused on the burden associated with individual large wildfires, but few have explored historical temporal trends in smoke-related burden in the context of total particulate air pollution, and population disparities in burden, at a large geographic scale.

What This Study Adds to the Field

We examined over 30 million cardiorespiratory-related emergency department and hospital visits in California between 2008 and 2016. While the total PM2.5-related burden declined steadily, the smoke-related burden varied with the size of the wildfire season, comprising as much as 15% of the total PM2.5-related health burden in a single year. Areas already experiencing higher total PM2.5 exposure, children, the elderly, and Black and Native American groups experienced higher smoke-related burden than others. Our study suggests wildfire smoke can significantly impede efforts to promote population health through improved air quality. Additionally, in California, most existing disparities in health burden and total PM2.5 exposure are preserved in the smoke-related health burden, exacerbating existing environmental injustices.

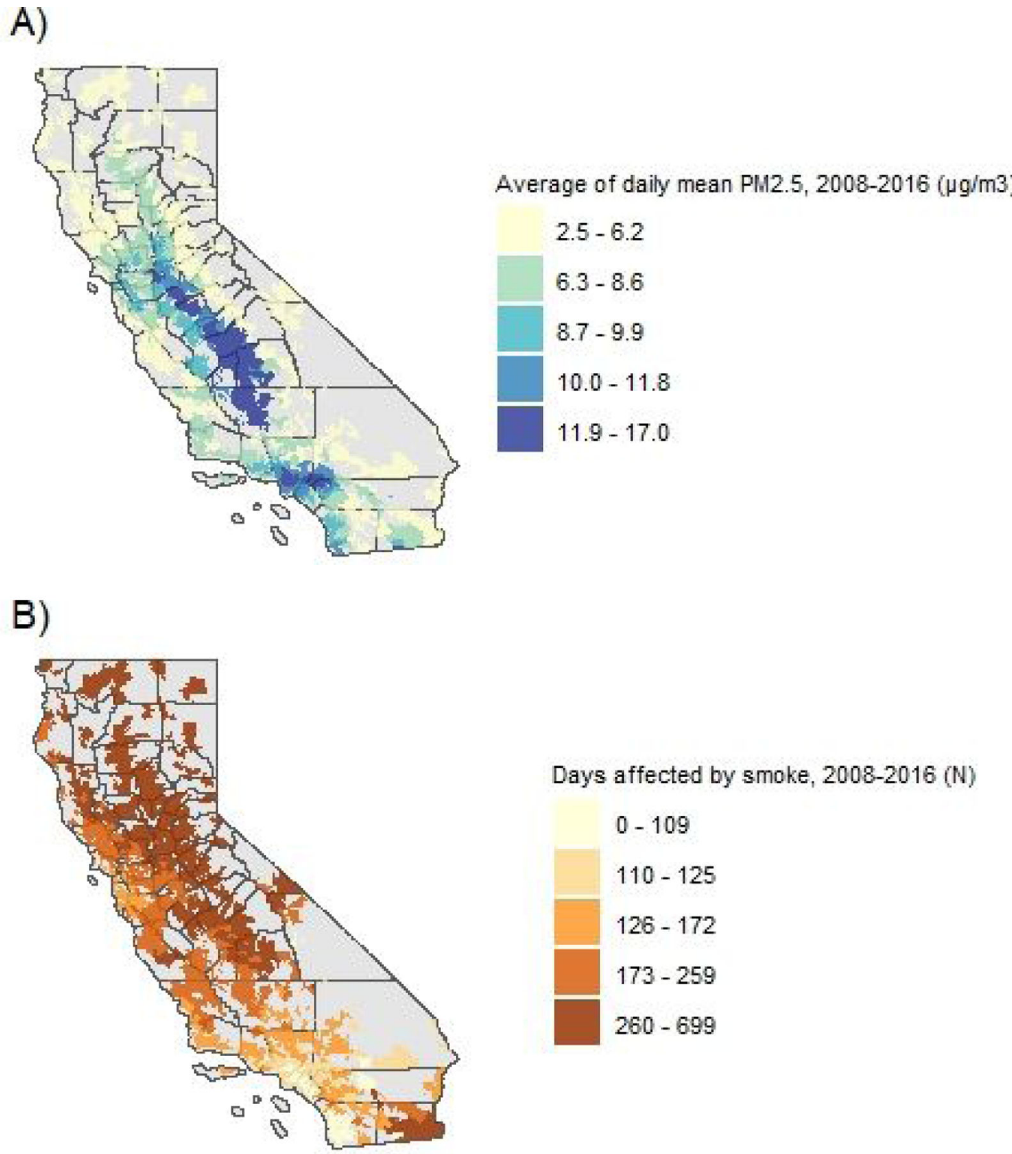
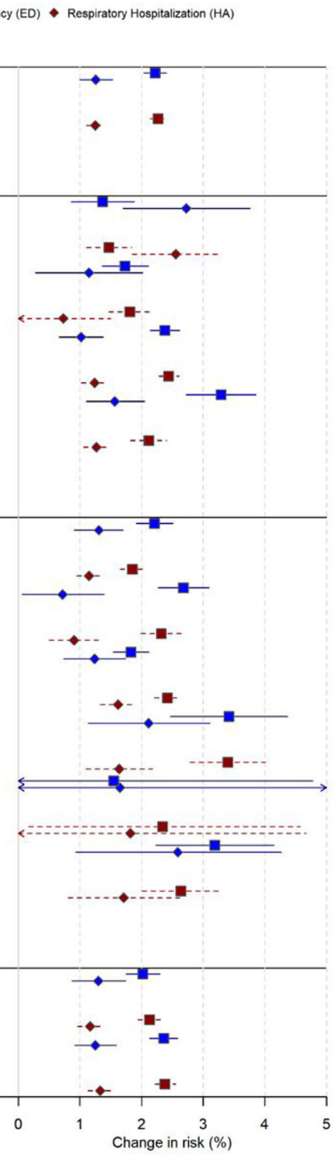


Figure 1.

Daily mean fine particulate matter ($PM_{2.5}$) concentrations on days where smoke was not detected (A), and the cumulative number of days on which smoke was detected (B), between 2008 and 2016. ZIP codes level maps are color coded by the quintiles of respective distributions and black boundaries denote counties.

	ED: Δ Risk (%) (95% CI)	HA: Δ Risk (%) (95% CI)
Asthma	2.22 (2.04, 2.40)	1.26 (1.00, 1.53)
Respiratory	2.27 (2.14, 2.39)	1.25 (1.11, 1.40)
Age		
0-4	1.37 (0.86, 1.88)	2.73 (1.70, 3.76)
	1.47 (1.11, 1.84)	2.56 (1.85, 3.28)
5-18	1.73 (1.36, 2.11)	1.15 (0.28, 2.02)
	1.81 (1.47, 2.15)	0.73 (-0.03, 1.50)
19-64	2.38 (2.14, 2.62)	1.02 (0.66, 1.38)
	2.44 (2.28, 2.61)	1.24 (1.02, 1.46)
65+	3.29 (2.72, 3.86)	1.57 (1.10, 2.05)
	2.12 (1.82, 2.41)	1.27 (1.06, 1.48)
Race/Ethnicity[a]		
White	2.21 (1.91, 2.51)	1.31 (0.91, 1.70)
	1.85 (1.65, 2.04)	1.15 (0.95, 1.35)
Black	2.68 (2.27, 3.10)	0.72 (0.06, 1.39)
	2.32 (1.99, 2.66)	0.91 (0.50, 1.33)
Hispanic	1.83 (1.54, 2.12)	1.24 (0.74, 1.74)
	2.42 (2.21, 2.63)	1.62 (1.33, 1.91)
Asian	3.42 (2.47, 4.37)	2.12 (1.14, 3.11)
	3.40 (2.79, 4.01)	1.64 (1.10, 2.18)
Native American	1.55 (-1.57, 4.78)	1.65 (-2.93, 6.45)
	2.34 (0.17, 4.57)	1.82 (-0.95, 4.67)
Other	3.19 (2.23, 4.15)	2.59 (0.93, 4.27)
	2.64 (2.01, 3.27)	1.71 (0.81, 2.62)
Sex		
Male	2.02 (1.75, 2.30)	1.30 (0.87, 1.74)
	2.13 (1.94, 2.31)	1.17 (0.96, 1.38)
Female	2.36 (2.13, 2.59)	1.25 (0.92, 1.59)
	2.38 (2.22, 2.55)	1.33 (1.13, 1.53)



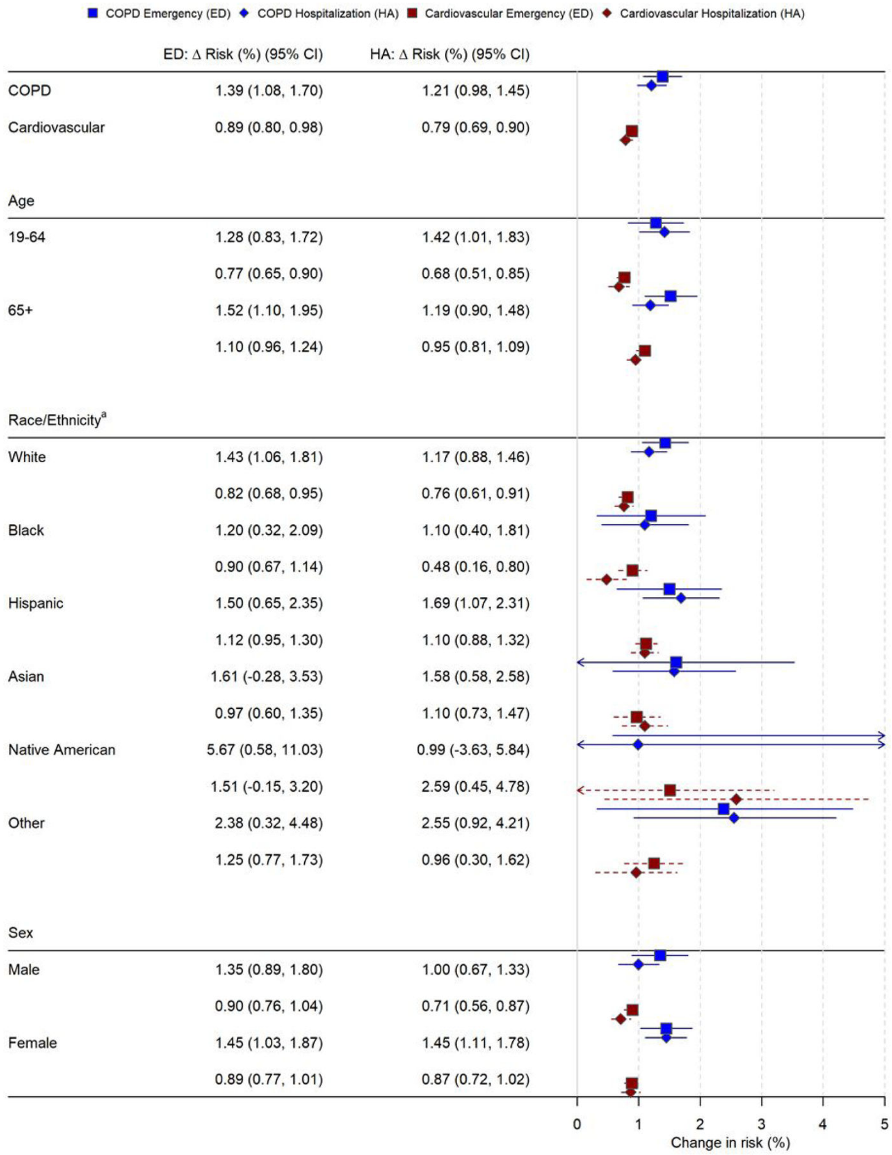


Figure 2.

Percent change in risk of emergency department visits and hospital admissions related to asthma and respiratory disease (A) and chronic obstructive pulmonary disease (COPD) and cardiovascular disease (B) per 10 μg/m^3 increase in fine particulate matter ($PM_{2.5}$), California, 2008–2016.

[a]Race/Ethnicity: White, Black, Asian, Native American, and Other categories are exclusive of Hispanic or Latino

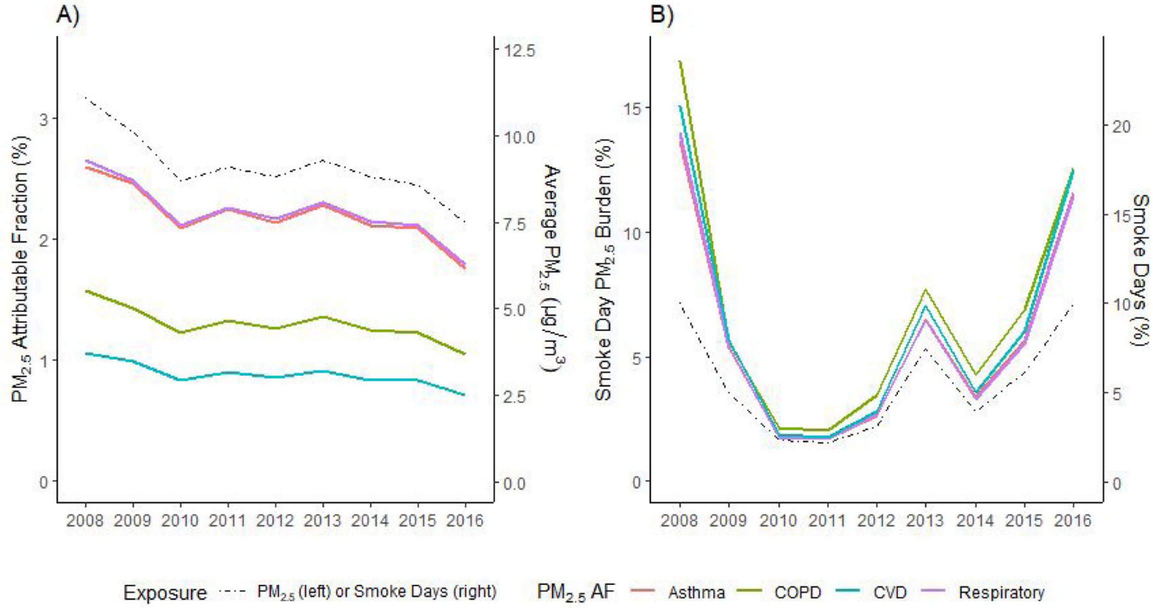


Figure 3.

Annual $PM_{2.5}$ attributable fraction (A) and percent of $PM_{2.5}$ burden on days with wildfire smoke (B), for emergency department visits related to asthma, chronic obstructive pulmonary disease (COPD), respiratory disease, and cardiovascular disease, California, 2008–2016.

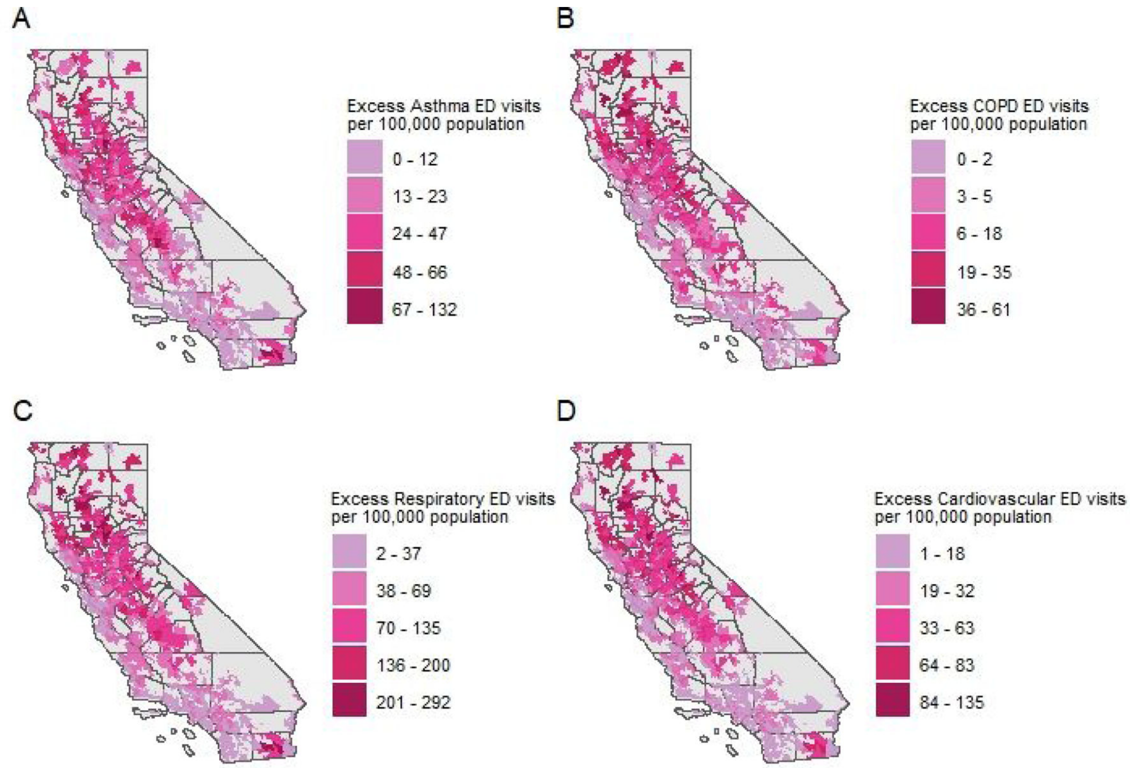


Figure 4.

$PM_{2.5}$ attributable rate of cardiorespiratory-related emergency department visits per 100,000 people on days affected by smoke, cumulatively over 2008–2016, at ZIP code resolution, for (A) asthma, (B) chronic obstructive pulmonary disease (COPD), (C) respiratory disease, and (D) cardiovascular disease. Color gradient is determined by the following percentile ranges of the ZIP code-level rates: 0–50, 50–75, 75–95, 95–99, and 99–100. Black boundaries denote counties.

Table 1.

Annual Emergency Department visit burden rates per 100,000 people for asthma, chronic obstructive pulmonary disease, respiratory disease, and cardiovascular disease, California, 2008–2016. Rates are given for the whole population and by demographic and geographic characteristics and expressed per 100,000 people in the subgroup. Percentage of visits shared by subpopulation are given in parentheses. California 2010 population fraction estimates are provided in the second column for reference.

	CA Population[b] (%)	Asthma Rate (%)	COPD Rate (%)	Respiratory Rate (%)	Cardiovascular Rate (%)
N (2008–2016)	37,366,938	4,991,726	1,548,881	13,816,258	15,120,404
Annual Visit					
Rate		1,513	469	4,186	4,582
Age Group					
0–4	6.8%	2,151(9.7)	NC	5,837 (9.5)	NC
5–18	19.6%	1,662 (21.5)	NC	2,714 (12.7)	NC
19–64	62.1%	1,404 (57.7)	332 (43.9)	3,916 (58.1)	3,961 (53.7)
65+	11.4%	1,479 (11.1)	2,298 (55.8)	7,242 (19.7)	18,422 (45.8)
Race/Ethnicity[a]					
White	40.3%	1,427 (38.0)	820 (70.4)	4,416 (42.5)	5,537 (48.7)
Black	5.9%	4,926 (19.2)	952 (12.0)	10,269 (14.5)	11,029 (14.2)
Hispanic	37.7%	1,336 (33.3)	135 (10.9)	3,550 (32.0)	3,060 (25.2)
Asian	13.3%	489 (4.3)	103 (2.9)	1,575 (5.0)	2,260 (6.6)
Native	0.4%	1,579 (0.4)	683 (0.5)	4,255 (0.4)	4,382 (0.4)
American					
Other	2.4%	2,290 (3.6)	442 (3.6)	7,156 (0.4)	7,019 (3.7)
Sex					
Male	49.7%	1,247 (41.0)	435 (46.0)	3,733 (44.3)	4,059 (44.0)
Female	50.3%	1,774 (59.0)	503 (54.0)	4,635 (55.7)	5,098 (56.0)
Urbanicity					
Urban	94.4%	1,499 (93.5)	438 (88.2)	4,117 (92.8)	4,525 (93.8)
Rural	5.6%	1,746 (6.5)	987 (11.8)	5,355 (7.2)	5,538 (6.8)
Long-term Air					
Quality					
$<12\ \mu g/m^3$	83.3%	1,483 (76.6)	495 (82.3)	4,147 (77.5)	4,615 (78.7)
$12+\ \mu g/m^3$	16.7%	1,615 (23.4)	382 (17.7)	4,321 (22.5)	4,468 (21.3)

CA: California; COPD: chronic obstructive pulmonary disease; NC: not calculated due to low counts

[a]Race/Ethnicity: White, Black, Asian, Native American, and Other categories are exclusive of Hispanic or Latino

[b]Estimates of demographic characteristics for the state of California are for the year 2010 and were derived from several data sources. Race/Ethnicity, sex, and age estimates are from the California Department of Finance. Urbanicity estimates are from the United States Department of Agriculture Rural-Urban Commuting Area Codes. Long-term air quality was determined by long-term averages of ZIP code-level satellite-based estimates of fine particulate matter ($PM_{2.5}$) on days when no wildland fire smoke was observed.

Table 2.

Annual Emergency Department visit rates per 100,000 people for asthma, chronic obstructive pulmonary disease (COPD), respiratory disease, and cardiovascular disease, attributed to $PM_{2.5}$ exposure, California, 2008–2016. Annual rates (95% confidence intervals) are given for the whole population and by demographic and geographic characteristics and expressed per 100,000 people in the subgroup. $PM_{2.5}$ attributable fraction is given in parentheses.

	Asthma Rate (%) (95% CI)	COPD Rate (%) (95% CI)	Respiratory Rate (%) (95% CI)	Cardiovascular Rate (%) (95% CI)
N (2008–2016)	107,493 (98,840, 116,169)	19,620 (15,246, 24,013)	302,262 (285,668, 318,887)	129,908 (116,565, 143,269)
Annual $PM_{2.5}$	33 (2.2)	6 (1.3)	92 (2.2)	39 (0.9)
Burden Rate	(29.9, 35.2)	(4.6, 7.3)	(86.6, 96.6)	(35.3, 43.4)
Age Group				
0–4	31 (1.5) (19.6, 43.0)	NC	89 (1.5) (67.5, 111.5)	NC
5–18	29 (1.7)	NC	49 (1.8) (67.5, 111.5)	NC
19–64	32 (2.3) (28.8, 35.2)	4 (1.2) (2.5, 5.3)	92 (2.4) (86.0, 98.5)	30 (0.8) (25.3, 34.9)
65+	44 (3.0) (36.7, 52.2)	32 (1.4) (22.8, 40.4)	141 (1.9) (121.3, 160.6)	191 (1.0) (167.0, 215.2)
Race/Ethnicity[a]				
White	28 (2.0) (24.4, 32.1)	10 (1.3) (7.6, 13.0)	73 (1.7) (65.5, 81.1)	41 (0.7) (33.9, 47.6)
Black	133 (2.7) (112.7, 154.2)	12 (1.2) (3.0, 20.1)	242 (2.4) (207.2, 277.0)	103 (0.9) (75.5, 129.5)
Hispanic	25 (1.9) (21.2, 29.3)	2 (1.5) (0.9, 3.2)	89 (2.5) (80.8, 96.1)	36 (1.2) (30.1, 41.1)
Asian	16 (3.3) (11.3, 20.1)	2 (1.9) (-0.3, 3.5)	51 (3.2) (41.6, 60.0)	22 (1.0) (13.2, 29.7)
Native American	19 (1.2) (-18.7, 57.6)	25 (3.6) (2.5, 48.2)	75 (1.8) (5.3, 146.1)	50 (1.1) (-5.0, 105.2)
Other	70 (3.1) (49.0, 91.4)	10 (2.2) (1.3, 18.7)	183 (2.6) (139.3, 227.0)	86 (1.2) (52.5, 118.9)
Sex				
Male	25 (2.0) (21.4, 28.2)	5 (1.2) (3.5, 7.2)	77 (2.1) (70.1, 83.6)	35 (0.9) (29.5, 40.3)
Female	40 (2.3) (36.4, 44.4)	7 (1.3) (4.7, 8.6)	106 (2.3) (98.8, 113.7)	44 (0.9) (38.1, 50.2)
Urbanicity				
Urban	33 (2.2) (30.4, 35.7)	6 (1.3) (4.5 7.2)	93 (2.2) (87.5, 97.7)	40 (0.9) (35.8, 44.0)
Rural	25 (1.4) (22.7, 26.6)	8 (0.8) (5.8, 9.2)	75 (1.4) (70.6, 78.8)	30 (0.5) (27.0, 33.1)
Long-term Air Quality				
<12 $\mu g/m^3$	29 (1.9) (26.2, 30.8)	6 (1.2) (4.4, 6.9)	81 (2.0) (76.8, 85.7)	36 (0.8) (32.2, 39.6)
12+ $\mu g/m^3$	47 (2.9) (42.7, 50.3)	7 (1.8) (5.4, 8.6)	127 (2.9) (120.0, 134.1)	51 (1.1) (46.0, 56.5)

CA: California; COPD: chronic obstructive pulmonary disease; NC: not calculated due to low counts

[a]Race/Ethnicity: White, Black, Asian, Native American, and Other categories are exclusive of Hispanic or Latino

Urbanicity estimates are from the United States Department of Agriculture Rural-Urban Commuting Area Codes. Long-term air quality was determined by long-term averages of ZIP code-level satellite-based estimates of fine particulate matter ($PM_{2.5}$) on days when no wildland fire smoke was observed.

Table 3.

Annual Emergency Department visit rates per 100,000 people for asthma, chronic obstructive pulmonary disease (COPD), respiratory disease, and cardiovascular disease, attributed to $PM_{2.5}$ exposure on days where air quality was affected by wildfire smoke (smoke days), California, 2008–2016. Annual rates (95% confidence intervals) are given for the whole population and by demographic and geographic characteristics and expressed per 100,000 people in the subgroup. Wildfire smoke-$PM_{2.5}$ attributable fraction is given in parentheses.

	Asthma Rate (%) (95% CI)	COPD Rate (%) (95% CI)	Respiratory Rate (%) (95% CI)	Cardiovascular Rate (%) (95% CI)
N (2008–2016)	6,167 (5,669, 6,666)	1,362 (1,058, 1,669)	17,614 (16,643, 18,587)	8,067 (7,237, 8,898)
Annual $PM_{2.5}$	1.9 (0.13)	0.4 (0.09)	5.4 (0.13)	2.5 (0.05)
Burden Rate	(1.7, 2.0)	(0.3, 0.5)	(5.1, 5.7)	(2.2, 2.7)
Age Group				
0–4	1.4 (0.07) (0.9, 2.0)	NC	3.7 (0.06) (2.8, 4.7)	NC
5–18	1.5 (0.09) (1.2, 1.8)	NC	2.5 (0.09) (2.1, 3.0)	NC
19–64	2.0 (0.14) (1.8, 2.2)	0.3 (0.09) (0.2, 0.4)	5.7 (0.15) (5.3, 6.1)	1.9 (0.05) (1.6, 2.2)
65+	2.7 (0.18) (2.3, 3.2)	2.2 (0.10) (1.6, 2.8)	8.9 (0.12) (7.7, 10.2)	11.8 (0.06) (10.3, 13.3)
Race/Ethnicity[a]				
White	1.9 (0.13) (1.6, 2.2)	0.8 (0.10) (0.6, 1.0)	4.9 (0.11) (4.4, 5.5)	2.8 (0.05) (2.3, 3.3)
Black	7.1 (0.14) (6.0, 8.3)	0.7 (0.07) (0.2, 1.2)	12.9 (0.13) (11.0, 14.8)	5.7 (0.05) (4.2, 7.2)
Hispanic	1.3 (0.10) (1.1, 1.5)	0.1 (0.07) (0.1, 0.2)	4.6 (0.13) (4.2, 4.9)	2.0 (0.07) (1.7, 2.3)
Asian	0.8 (0.16) (0.6, 1.1)	0.1 (0.10) (0, 0.2)	2.8 (0.17) (2.3, 3.3)	1.2 (0.05) (0.7, 1.7)
Native American	1.6 (0.10) (-1.6, 5.0)	2.4 (0.35) (0.2, 4.9)	6.5 (0.15) (0.5, 12.7)	4.6 (0.10) (-0.5, 9.7)
Other	3.6 (0.16) (2.5, 4.7)	0.6 (0.14) (0.1, 1.1)	9.4 (0.13) (7.1, 11.6)	4.7 (0.07) (2.9, 6.5)
Sex				
Male	1.4 (0.11) (1.2, 1.6)	0.4 (0.09) (0.2, 0.5)	4.4 (0.12) (4.0, 4.8)	2.2 (0.05) (1.8, 2.5)
Female	2.4 (0.14) (2.1, 2.6)	0.5 (0.10) (0.3, 0.6)	6.3 (0.14) (5.8, 6.7)	2.7 (0.05) (2.4, 3.1)
Urbanicity				
Urban	1.8 (0.12) (1.7, 2.0)	0.4 (0.09) (0.3, 0.4)	5.1 (0.12) (4.8, 5.4)	2.3 (0.05) (2.1, 2.6)
Rural	3.0 (0.17) (2.8, 3.3)	1.2 (0.12) (0.9, 1.5)	9.8 (0.18) (9.3, 10.4)	4.4 (0.08) (3.9, 4.8)
Long-term Air Quality				
$<12\ \mu g/m^3$	1.7 (0.11) (1.6, 1.9)	0.4 (0.08) (0.3, 0.5)	5.0 (0.12) (4.7, 5.3)	2.3 (0.05) (2.1, 2.6)
$12+\ \mu g/m^3$	2.3 (0.14) (2.2, 2.5)	0.4 (0.10) (0.3, 0.5)	6.5 (0.15) (6.2, 6.9)	2.8 (0.06) (2.5, 3.1)

CA: California; COPD: chronic obstructive pulmonary disease; NC: not calculated due to low counts

[a]Race/Ethnicity: White, Black, Asian, Native American, and Other categories are exclusive of Hispanic or Latino

Urbanicity estimates are from the United States Department of Agriculture Rural-Urban Commuting Area Codes. Long-term air quality was determined by long-term averages of ZIP code-level satellite-based estimates of fine particulate matter ($PM_{2.5}$) on days when no wildland fire smoke was observed.