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Wildfire particulate matter in Shasta County, California and respiratory and circulatory disease-related emergency department visits and mortality, 2013–2018

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Background: Wildfire smoke harms health. We add to this literature by evaluating the health effects of California's 2018 Carr Fire and preceding wildfire seasons in Shasta County.

Methods: With data from the Shasta County Health and Human Services Agency, we examined the link between weekly wildfire fine particulate matter ($PM_{2.5}$) exposure estimated using a spatiotemporal multiple imputation approach and emergency department (ED) visits and mortality using time-series models that controlled for temporal trends and temperature.

Results: Between 2013 and 2018, Shasta County experienced 19 weeks with average wildfire $PM_{2.5} \geq 5.5$ μg/m^3 (hereafter, "high wildfire $PM_{2.5}$ concentration"). Among all Shasta County Zip Code Tabulation Areas (ZCTAs; n = 36), we detected no association between high wildfire $PM_{2.5}$ concentrations and respiratory or circulatory disease-related ED visits or mortality. Subsequent analyses were confined to valley ZCTAs (n = 11, lower elevation, majority of population, worse air quality in general). In valley ZCTAs, high wildfire $PM_{2.5}$ was associated with a 14.6% (95% confidence interval [CI] = 4.2, 24.9) increase in same-week respiratory disease-related ED visits but no increase in the subsequent 2 weeks nor on circulatory disease-related mortality or ED visits or all-cause mortality. Two weeks after high wildfire $PM_{2.5}$ weeks, respiratory disease-related deaths decreased (–31.5%, 95% CI = –64.4, 1.5). The 2018 Carr Fire appeared to increase respiratory disease-related ED visits by 27.0% (95% CI = 4.0, 50.0) over expectation and possibly reduce circulatory disease-related deaths (–18.2%, 95% CI = –39.4, 2.9).

Conclusions: As climate change fuels wildfire seasons, studies must continue to evaluate their health effects, particularly in highly exposed populations.

Keywords: Wildfires; Smoke; Cause of death; Respiratory tract diseases; California; Emergency service; Hospital; Air pollution

Introduction

In California, wildfires account for 71% of total fine particulate matter ($PM_{2.5}$) on days that exceed US Environmental Protection Agency (USEPA) standards.[1] This proportion will likely increase in the future. In addition to $PM_{2.5}$, wildfires generate volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and trace metals and contribute to elevated ozone levels, all of which potentially harm health.[2–4] Global research suggests a relationship between wildfire smoke exposure and respiratory disease-related emergency department (ED) visits, but evidence is mixed regarding circulatory disease-related ED visits and cause-specific mortality.[5–14] We know of no studies that evaluate health implications of California's 2018 wildfire season, one of its most destructive to date.

Methods

We used data from the Shasta County Health and Human Services Agency from January 2013 to December 2018 to assess associations between Zip Code Tabulation Areas (ZCTAs)

What this study adds

California experienced one of its worst wildfire seasons ever in 2018. The Carr Fire in Shasta County burned nearly 230,000 acres, destroyed over 1,500 homes, and cost $162 million to contain. This study provides the first evidence of an association between smoke from the 2018 wildfires and morbidity and mortality in human populations. In the most populated, low-elevation areas, we found that increased weekly wildfire particulate matter ($PM_{2.5}$) was associated with respiratory disease-related emergency department (ED) visits, but not circulatory disease-related ED visits or all-cause or respiratory disease- or circulatory disease-related deaths. Similarly, the Carr Fire itself appeared to result in increased respiratory disease-related ED visits.

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Data access: Exposure data are available on GitHub: https://github.com/joanacasey/shastafire/. Health data may be available upon request from the Shasta County Health and Human Services.

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weekly average wildfire $PM_{2.5}$ and ED visits and mortality. We specifically evaluated the Carr Fire, among California's most destructive fires, which ignited on 23 July 2018 and burned nearly 230,000 acres in Shasta and Trinity Counties before it was contained on 30 August 2018 and extinguished in January 2019. Located in Northern California, Shasta County is mountainous (minimum elevation = 43 m; maximum elevation = 4,247 m) and relatively rural with an overall population density of ~19 individuals per km^2. It contains 36 ZCTAs, which can be grouped into 11 valley (lower elevation, majority of population [~88%], worse air quality in general) and 25 mountain ZCTAs (eTable 1; http://links.lww.com/EE/A113 and eFigure 1; http://links.lww.com/EE/A113).

We identified weekly counts of respiratory and circulatory disease-related ED visits and all-cause and respiratory and circulatory disease-related mortality using *International Classification of Diseases* codes (460–519 [*ICD*-9] and J00–J99 [*ICD*-10] and 390–459 [*ICD*-9] and I00–I99 [*ICD*-10], respectively) for Shasta County residents.

To estimate daily ZIP code-level wildfire and nonwildfire $PM_{2.5}$ concentrations, we used a multistage approach (see eMethods; http://links.lww.com/EE/A113). Briefly, we first identified smoke-plume exposed ZIP codes/days with the National Oceanic and Atmospheric Administration's (NOAA) Hazard Mapping System (HMS) and overall $PM_{2.5}$ concentrations with USEPA monitoring data from the Redding and Lassen stations and then used a spatiotemporal multiple imputation approach to estimate daily ZIP code-level wildfire $PM_{2.5}$ concentrations, which we aggregated to the weekly-level for analyses. We estimated the intraclass correlation coefficient for the ZIP code-specific wildfire $PM_{2.5}$ concentrations—the ratio of the between ZIP code over the sum of the within-ZIP code contributions to total variability—as 0.01. This indicated the majority of variation in wildfire $PM_{2.5}$ occurred over time, rather than across ZIP codes (eFigure 2; http://links.lww.com/EE/A113). This fact and because Shasta County has low population density resulting in low ZCTA-level counts of health outcomes, we conducted weekly analyses across all ZCTAs combined and then restricted to ZCTAs in the valley. We defined weeks in which wildfire $PM_{2.5}$ equaled or exceeded the study period mean concentration of 5.5 $\mu g/m^3$ as high wildfire $PM_{2.5}$ weeks. We selected this level, which represented the mean nonzero wildfire $PM_{2.5}$ concentration a priori. We also linked weekly average maximum temperature from NOAA's Local Climatological Data Daily Summary from the Redding, CA station. Redding is the largest city in Shasta County: over 50% of residents overall and 68% of residents in valley Zip Code Tabulation Areas (ZCTAs) live there.

For analyses, we used Box-Jenkins transfer function models[15] to estimate the association between time-series measuring weekly average wildfire $PM_{2.5}$ concentrations and the logarithm of respiratory and circulatory disease-related ED visits and all-cause and respiratory and circulatory disease-related mortality. This approach detects and controls autocorrelation—including trends, cycles, and persistence of high and low observations—that can lead to spurious associations arising from shared autocorrelation (e.g., seasonality) and make estimates of true associations less precise. Because Shasta County has low population density resulting in low ZCTA-level counts of health outcomes, we conducted weekly analyses across all ZCTAs combined and then restricted to ZCTAs in the valley.

We estimated the relationship between wildfire $PM_{2.5}$ and health outcomes in two ways. First, we estimated the association between weekly $PM_{2.5}$ ≥5.5 $\mu m/m^3$ (hereafter, "high wildfire $PM_{2.5}$") and outcomes. Second, we specified a binary "Carr Fire" variable equal to 1 during the Carr Fire and 0 otherwise. Because our outcome was log(Y), model coefficients approximate the percent change in each outcome when wildfire $PM_{2.5}$ was high. All tests controlled for temperature and adjusted outcomes for autocorrelation.

Results

This study included 36 ZCTAs containing approximately 180,000 residents of Shasta County, California, between 2013 and 2018, when 51 major wildfires (>5,000 acres burned) occurred within 100 km of the County. Between 2013 and 2018, Shasta County experienced 19 weeks with average wildfire $PM_{2.5}$ ≥5.5 $\mu g/m^3$. Wildfire $PM_{2.5}$ concentrations reached their weekly average maximum (48 $\mu g/m^3$) during the 2018 Carr Fire (Figure A). Maximum average weekly temperature followed a seasonal pattern, with an annual average of 25.6 °C. Across the 314-week study period, there were a weekly average (SD) of 142 (64) respiratory disease-related ED visits, 31 (7) circulatory disease-related ED visits, 35 (7) all-cause deaths, 5 (2) respiratory disease-related deaths, and 11 (3) circulatory disease-related deaths. Respiratory disease-related ED visits exhibited strong seasonality (Figure B), whereas other outcomes did not.

We observed no associations between weekly high wildfire $PM_{2.5}$ or the Carr Fire and ED visits or deaths overall. However, in models restricted to valley ZCTAs (n = 11), weekly high wildfire $PM_{2.5}$ was associated with a 14.6% (95% confidence interval [CI] = 4.2, 24.9) increase in respiratory disease-related ED visits in the same week but no increase the subsequent 2 weeks (eTable 2; http://links.lww.com/EE/A113). We observed no association between high wildfire $PM_{2.5}$ and circulatory disease-related ED visits or all-cause or circulatory disease-related mortality. High wildfire $PM_{2.5}$ was potentially associated with decreased respiratory disease-related deaths 2 weeks later (–31.5%, 95% CI = –64.4, 1.5).

The Carr Fire appeared to increase respiratory disease-related ED visits by 27.0% (95% CI = 4.0, 50.0) over expectation, with no association for circulatory disease-related ED visits and all-cause deaths or respiratory disease-related deaths, and a potentially protective association with circulatory disease-related deaths (–18.2%, 95% CI = –39.4, 2.9).

Further adjustment of models for weekly average nonwildfire $PM_{2.5}$ did not materially change results. For example, we observed a 14.7% (95% CI = 1.6, 27.7) increase in respiratory disease-related ED visits during weeks where wildfire $PM_{2.5}$ was ≥5.5 $\mu g/m^3$.

Discussion

We observed a 14.6% increase in respiratory disease-related ED visits in weeks where wildfire $PM_{2.5}$ was ≥5.5 $\mu g/m^3$ in valley ZCTAs of Shasta County, CA, between 2013 and 2018, with a 27.0% increase during the 2018 Carr Fire. No associations were seen for circulatory disease-related ED visits or all-cause or circulatory or respiratory disease-related deaths.

Our sample size precluded examination of specific respiratory and circulatory diseases, but results were consistent with three prior studies that reported associations between wildfire smoke and combined respiratory visits in California.[6,16,17] Prior research has consistently demonstrated increased risk of asthma- and chronic obstructive pulmonary disease-related ED visits associated with increased wildfire $PM_{2.5}$.[5,6,16,18,19] For example, prior studies have reported associations between 3-day average wildfire $PM_{2.5}$ and respiratory disease-related ED visits[18] and subdaily overall $PM_{2.5}$ during wildfire season and ambulance dispatches for adverse respiratory outcomes.[13] We were unable to assess relevant daily or subdaily lagged results due to a relatively small population (approximately 190,000 people) and sparse daily counts. This is a limitation that may have contributed to our null results for all outcomes other than respiratory ED visits. Further, average weekly versus daily nonwildfire $PM_{2.5}$ and maximum temperature may not adequately control confounding by these factors. Other studies that have taken a similar approach to ours, but at the daily level, have identified increases in daily respiratory ED visits[19,20] and adverse

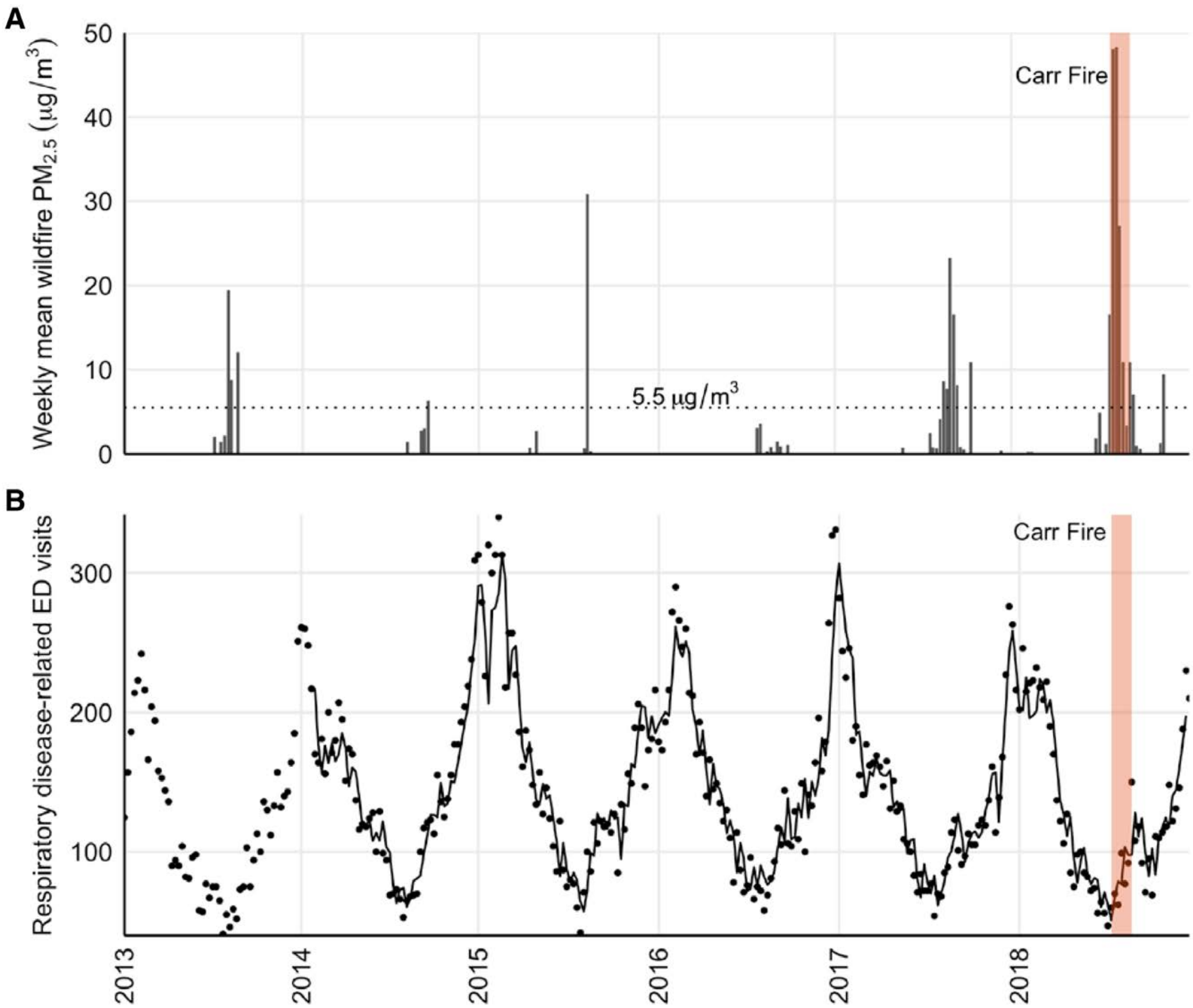

Figure. Weekly data in Shasta County, California valley Zip Code Tabulation Areas from January 2013 to December 2018. A, Weekly mean wildfire $PM_{2.5}$ concentration and (B) observed (points) and expected (lines) respiratory disease-related ED visits. The orange rectangle denotes the weeks of the 2018 Carr Fire.

respiratory effects of specific wildfires, including the 2017 California Lilac Fire[12] and the Fall 2007 California firestorm,[6] for example.

Importantly, our analyses controlled for weekly average maximum temperature. The average maximum temperature exceeded 41 °C (106 °F) during the first week of the Carr Fire. Higher temperatures could have exacerbated the effect of the fire, as observed during the 2010 Moscow heatwave and wildfire,[21] or could have encouraged residents to stay indoors, thereby reducing exposure. We were unable to consider the role of other potentially important wildfire-related air pollutant exposures beyond $PM_{2.5}$, including VOCs, PAHs, or secondarily formed ozone. In mutually adjusted models, Reid et al[16] found $PM_{2.5}$, but not ozone, was associated with increased asthma-related ED visits during a large 2008 California wildfire. However, ozone levels do increase during wildfires and may impact health in some cases. In addition, by examining total wildfire $PM_{2.5}$, we capture an overall wildfire mixture, but could not know which specific components of $PM_{2.5}$ were related to the outcomes of interest.

As climate change fuels more frequent and destructive wildfires,[1,22] studies must continue to evaluate their health effects, particularly in highly exposed populations. Future studies may wish to consider compounding environmental and social effects of wildfire $PM_{2.5}$ with other exposures such as extreme heat, co-occurring air pollution, or low socioeconomic status. In addition, characterizing population mobility such as evacuation and other responses to wildfire warning systems has the potential to inform wildfire policy and preparedness to reduce adverse health effects.

Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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References

1. Liu JC, Mickley LJ, Sulprizio MP, et al. Particulate air pollution from wildfires in the Western US under climate change. Clim Change. 2016;138:655–666.
2. Jaffe DA, Wigder N, Downey N, Pfister G, Boynard A, Reid SB. Impact of wildfires on ozone exceptional events in the Western U.S. Environ Sci Technol. 2013;47:11065–11072.
3. Adetona O, Reinhardt TE, Domitrovich J, et al. Review of the health effects of wildland fire smoke on wildland firefighters and the public. Inhal Toxicol. 2016;28:95–139.

4. Ford B, Val Martin M, Zelasky SE, et al. Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. Geohealth. 2018;2:229–247.
5. 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.
6. Hutchinson JA, Vargo J, Milet M, et al. The San Diego 2007 wildfires and Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: an observational study of smoke exposure periods and a bidirectional case-crossover analysis. PLoS Med. 2018;15:e1002601.
7. Cascio WE. Wildland fire smoke and human health. Sci Total Environ. 2018;624:586–595.
8. Doubleday A, Schulte J, Sheppard L, et al. Mortality associated with wildfire smoke exposure in Washington state, 2006-2017: a case-crossover study. Environ Health. 2020;19:4.
9. Borchers-Arriagada N, Palmer AJ, Bowman D, Williamson GJ, Johnston FH. Health impacts of ambient biomass smoke in Tasmania, Australia. Int J Environ Res Public Health. 2020;17:3264.
10. Borchers Arriagada N, Horsley JA, Palmer AJ, Morgan GG, Tham R, Johnston FH. Association between fire smoke fine particulate matter and asthma-related outcomes: systematic review and meta-analysis. Environ Res. 2019;179(pt A):108777.
11. Haikerwal A, Akram M, Sim MR, Meyer M, Abramson MJ, Dennekamp M. Fine particulate matter (PM2.5) exposure during a prolonged wildfire period and emergency department visits for asthma. Respirology. 2016;21:88–94.
12. Leibel S, Nguyen M, Brick W, et al. Increase in pediatric respiratory visits associated with Santa Ana wind-driven wildfire smoke and PM2.5 levels in San Diego County. Ann Am Thorac Soc. 2020;17:313–320.
13. Yao J, Brauer M, Wei J, McGrail KM, Johnston FH, Henderson SB. Sub-daily exposure to fine particulate matter and ambulance dispatches during wildfire seasons: a case-crossover study in British Columbia, Canada. Environ Health Perspect. 2020;128:67006.
14. Kollanus V, Tiittanen P, Niemi JV, Lanki T. Effects of long-range transported air pollution from vegetation fires on daily mortality and hospital admissions in the Helsinki metropolitan area, Finland. Environ Res. 2016;151:351–358.
15. Catalano R, Serxner S. Time series designs of potential interest to epidemiologists. Am J Epidemiol. 1987;126:724–731.
16. Reid CE, Considine EM, Watson GL, Telesca D, Pfister GG, Jerrett M. Associations between respiratory health and ozone and fine particulate matter during a wildfire event. Environ Int. 2019;129:291–298.
17. Reid CE, Jerrett M, Tager IB, Petersen ML, Mann JK, Balmes JR. Differential respiratory health effects from the 2008 northern California wildfires: a spatiotemporal approach. Environ Res. 2016;150:227–235.
18. Stowell JD, Geng G, Saikawa E, et al. Associations of wildfire smoke $PM_{2.5}$ exposure with cardiorespiratory events in Colorado 2011-2014. Environ Int. 2019;133(pt A):105151.
19. Kiser D, Metcalf WJ, Elhanan G, et al. Particulate matter and emergency visits for asthma: a time-series study of their association in the presence and absence of wildfire smoke in Reno, Nevada, 2013-2018. Environ Health. 2020;19:92.
20. Tham R, Erbas B, Akram M, Dennekamp M, Abramson MJ. The impact of smoke on respiratory hospital outcomes during the 2002-2003 bushfire season, Victoria, Australia. Respirology. 2009;14:69–75.
21. Shaposhnikov D, Revich B, Bellander T, et al. Mortality related to air pollution with the moscow heat wave and wildfire of 2010. Epidemiology. 2014;25:359–364.
22. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci U S A. 2016;113:11770–11775.