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Original Contribution

Who Among the Elderly Is Most Vulnerable to Exposure to and Health Risks of Fine Particulate Matter From Wildfire Smoke?

Jia Coco Liu*, Ander Wilson, Loretta J. Mickley, Keita Ebisu, Melissa P. Sulprizio, Yun Wang, Roger D. Peng, Xu Yue, Francesca Dominici, and Michelle L. Bell

* Correspondence to Dr. Jia Coco Liu, Department of Biostatistics, Bloomberg School of Public Health, Johns Hopkins University, Room 3137, 615 N. Wolfe Street, Baltimore, MD 21205 (e-mail: coco.liu@jhu.edu).

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Wildfires burn more than 7 million acres in the United States annually, according to the US Forest Service. Little is known about which subpopulations are more vulnerable to health risks from wildfire smoke, including those associated with fine particulate matter. We estimated exposure to fine particles specifically from wildfires, as well as the associations between the presence of wildfire-specific fine particles and the amount of hospital admissions for respiratory causes among subpopulations older than 65 years of age in the western United States (2004–2009). Compared with other populations, higher fractions of persons who were black, lived in urban counties, and lived in California were exposed to more than 1 smoke wave (high-pollution episodes from wildfire smoke). The risks of respiratory admissions on smoke-wave days compared with non–smoke-wave days increased 10.4% (95% confidence interval: 1.9, 19.6) for women and 21.7% (95% confidence interval: 0.4, 47.3) for blacks. Our findings suggest that increased risks of respiratory admissions from wildfire smoke was significantly higher for women than for men (10.4% vs. 3.7%), blacks than whites (21.7% vs. 6.9%), and, although associations were not statistically different, people in lower-education counties than higher-educated counties (12.7% vs. 6.1%). Our study raised important environmental justice issues that can inform public health programs and wildfire management. As climate change increases the frequency and intensity of wildfires, evidence on vulnerable subpopulations can inform disaster preparedness and the understanding of climate change consequences.

air pollution; health; $PM_{2.5}$; respiratory outcomes; vulnerability; wildfire smoke

Abbreviations: $PM_{2.5}$, fine particulate mater with aerodynamic diameter greater than 2.5 μm; SES, socioeconomic status.

Climate change is anticipated to increase the frequency, intensity, and spreading speed of wildfires. In addition to property damage and expenditures on fire suppression and recovery, wildfire smoke dramatically worsens air pollution, especially by increasing levels of fine particulate mater with aerodynamic diameter greater than 2.5 μm ($PM_{2.5}$) (1, 2). Wildfire smoke can increase $PM_{2.5}$ levels to several times those seen during nonwildfire periods (3). Because wildfire-specific $PM_{2.5}$ might have chemical compositions and/or uniquely high concentrations of specific chemicals that differ from those of $PM_{2.5}$ from other sources, it could impose a different health-response function on exposed populations.

Some subpopulations may be particularly vulnerable to health risks from wildfire smoke because of biophysical and/or socioeconomic conditions (4). Older persons may have degraded immune systems (3, 5–9). Socioeconomic status (SES) or other demographic characteristics can be associated with exposure or the ability to adapt to environmental exposure (4, 10). Sex or race may be associated with occupation or activity patterns that lead to different environmental exposures (11). There have been few studies in which investigators have assessed vulnerability from wildfire pollution, and the results were inconsistent (3).

METHODS

We estimated $PM_{2.5}$ concentrations specifically from wildfires and from nonfire sources (2004–2009) in 561 counties

in the western United States (Web Figure 1, available at https://academic.oup.com/aje) by using the GEOS-Chem, version v9-01-03 (http://acmg.seas.harvard.edu/geos/) global chemical transport model and utilizing reports of daily emissions from the Global Fire Emissions Database (12). Details on GEOS-Chem modeling and validation can be found elsewhere (13). We converted GEOS-Chem's gridded estimation (resolution ≈0.5° latitude × 0.67° longitude) to county-level estimates by using area-weighted averaging. Wildfire-specific $PM_{2.5}$ estimates were calibrated with monitoring data (13, 14).

In our previous study, we found that hospital admissions for respiratory problems among persons older than 65 years of age were 7.2% (95% confidence interval: 0.25, 14.6) higher on smoke-wave days than on non–smoke-wave days, when a smoke wave was defined as a period with more than 2 consecutive days with daily calibrated wildfire-specific $PM_{2.5}$ concentrations greater than 37 $\mu g/m^3$ (13). Using Medicare claims data, we calculated total respiratory admissions as the sum of admissions for primary disease discharge codes of chronic obstructive pulmonary disease and respiratory tract infections (*International Classification of Diseases, Ninth Revision*, codes 490–492, 464–466, 480–487).

We classified each day in each county as a smoke-wave or non–smoke-wave day. Each smoke-wave day was matched with up to 3 non–smoke-wave days in the same county that occurred within the 7-day window before and after the smoke-wave day primarily in a different year and were separated from any other smoke-wave day by more than 2 days. We selected control days at random from among eligible control days for a given smoke-wave day to avoid a systematic pattern as to whether the matched days occurred before or after the smoke-wave day. When 3 eligible control days were not available, we used 1 or 2 days.

We categorized subpopulations by the following: 1) individual characteristics, including age (65–74, 75–84, or >85 years), sex, and race (black, white, or other); and 2) county characteristics, including education (<20% of elderly with bachelor's degree vs. ≥20% of elderly with bachelor's degree) (15), poverty rate (<10%, 10%–15%, or >15%) (16), urbanicity, and region (Web Appendix 1, Web Figure 1).

We assessed vulnerability for each subpopulation by the following: 1) exposure to smoke waves (2004–2009): proportion of exposed to more than 1 smoke wave, average number of smoke-wave days, and average intensity of smoke waves (Web Appendix 2); and 2) health risks from smoke waves: increase in respiratory admissions associated with smoke waves.

To estimate the associations of smoke-wave days with hospital admissions for respiratory conditions stratified by individual-level characteristics, we fitted a log-linear Poisson mixed-effects regression model for respiratory admissions across all 561 counties, with a term for the interaction between an indicator for smoke-wave day and an indicator for the specific subpopulation that controlled for nonfire $PM_{2.5}$ concentration, temperature, age, sex, race, and study year (Web Appendix 3). To estimate associations of smoke-wave exposure with hospital admissions for respiratory causes categorized by community-level characteristics, we stratified counties by community characteristics and fitted separate models for each stratum (Web Appendix 4). We then compared the associations in different subpopulations (17).

RESULTS

The total number of Medicare enrollees in the western United States from 2004 to 2009 was approximately 5 million (Table 1). Admission rates for respiratory illness were highest among persons in the oldest age group, among blacks, in counties with a poverty rate above 15%, and in counties in which

Table 1. Categorization of Subpopulation Based on Individual Characteristics, Population in These Groups, and Population Exposed to at Least 1 Smoke Wave in Each Subpopulation in Western US Counties, 2004–2009

Individual Characteristic	Average Population		Average No. Exposed to >1 Smoke Wave	% Subpopulation Exposed to >1 Smoke Wave[b]	Average No. of Smoke-Wave Days per Year	Average Smoke Wave Intensity, $\mu g/m^3$
	No.[a]	% of Total Population				
Age, years						
65–74	2,700,367	54.5	1,604,366	59.4	1.51	44.06
75–84	1,643,695	33.1	966,542	58.8	1.56	44.10
>84	614,865	12.4	391,847	63.7	1.62	44.13
Sex						
Female	2,743,008	55.3	1,641,338	59.8	1.55	44.11
Male	2,215,919	44.7	1,321,416	59.6	1.52	44.06
Race						
Black	157,934	3.2	115,933	73.4	1.77	43.95
White	4,110,641	82.9	2,302,364	56.0	1.47	44.01
Other	690,352	13.9	544,457	78.9	1.91	44.45

[a] The average Medicare population in each subpopulation during the study period. The Medicare population changes over time; values here represent the population size on an average day during the study period.

[b] Interpretation example: Of people 65–74 years of age, 59.4% were exposed to smoke waves during the study period compared with 58.8% of people 75–84 years of age.

less than 20% of the population had bachelor's degrees (Web Table 1). Some SES characteristics were correlated (Web Table 2). For example, counties with high fractions of black persons were more likely to be urban.

Smoke-wave exposure differed by subpopulations (Table 1). Approximately 73.4% of blacks were exposed to more than 1 smoke wave, compared with 56.0% of whites. Nearly all participants in California (99.2%) were exposed to more than 1 smoke wave, compared with 7.49% in the southwestern United States. Larger proportions of participants in urban counties (64.8% vs. 47.1% of participants in less-urban/rural counties) and more educated counties (63.3% vs. 49.8% for participants in less-educated counties) were exposed to more than 1 smoke wave (Web Table 3). The proportion exposed decreased as poverty decreased: The proportions were 61.5%, 56.2%, and 55.9% for persons living in counties with more than 15%, 10%–15%, and less than 10% of the population in poverty, respectively.

California had 4.08 smoke-wave days per year, the highest among the 4 regions (Web Table 3). The poorest counties (>15% people living in poverty) had the highest number of smoke-wave days/year (2.70 days per year on average compared with 1.28 days per year for counties with <10% people living in poverty).

We also assessed the intensity of smoke waves by measuring the average wildfire-specific $PM_{2.5}$ levels on smoke-wave days. Smoke waves in the Northern Rocky Mountains were the most intense (mean $PM_{2.5}$ concentration = 47.83 $\mu g/m^3$) compared with those elsewhere (in the Southwest, mean = 40.60 $\mu g/m^3$; Web Table 3). Although a smaller fraction of people in less-urban/rural counties was exposed to more than 1 smoke wave (47.1%) than in urban counties (64.8%), smoke-wave intensity was higher in less-urban/rural counties (mean = 47.01 $\mu g/m^3$) than in urban counties (mean = 43.85 $\mu g/m^3$). Smoke-wave intensity did not differ much by individual-level characteristics.

Results provided suggestive evidence that women (compared with men) and blacks (compared with whites or persons of other races) had higher risks of hospital admissions for respiratory illness associated with exposure to smoke waves (Table 2). The central estimate of relative risk of respiratory admissions on smoke-wave days compared with non–smoke-wave days was higher for people living in less-educated counties (for counties in which <20% of the elderly had a bachelor's degree, relative risk = 1.13, 95% confidence interval: 0.97, 1.31) than that of people living in more-educated counties (for counties in which ≥20% of the elderly had a bachelor's degree, relative = 1.06, 95% confidence interval: 0.98, 1.14). No subpopulation had a health risk that was significantly different from those of its counterparts in the respective characteristic categories.

DISCUSSION

Our study filled in important scientific gaps on wildfire and population health and addressed many challenges in characterizing vulnerability to wildfire smoke, such as the typically small sample sizes of subpopulations, difficulty in determining exposure to wildfire smoke, and the low frequency and geographical coverage of monitor measurements. In most previous studies on vulnerability to wildfire smoke, researchers investigated small numbers of communities exposed to single fire episodes. In our multiyear, multistate study, we considered a population of approximately 5 million and incorporated both urban and rural counties, which allowed us to estimate health risks by subpopulation and region. The present research is the first wildfire vulnerability study in which daily source-specific exposure estimates that distinguish wildfire-specific $PM_{2.5}$ from $PM_{2.5}$ from other sources in all western US counties were used. Instead of using "hot spots" from satellite images or rough start/end days of recorded wildfires, we utilized a new approach to define smoke days by using source-specific $PM_{2.5}$.

The present study has limitations. Although our study is the largest wildfire vulnerability study to date, we only focused on the elderly population. Previous research has indicated that preexisting medical conditions could be related to a vulnerability to the association between air pollution and health (18, 19), which could be investigated in relation to wildfire smoke in future studies. In future work, researchers can also investigate wildfire vulnerability with other ages or individual-level SES data. In addition, the correlation among variables hinders our ability to disentangle their associations with respect to variability.

Wildfire-related pollution is potentially an environmental justice issue because of the disparities in wildfire-smoke exposures and health responses, as well as the options to adapt (e.g., via accessing medical care and making lifestyle changes). In our study, we demonstrated important policy implications of this environmental justice issue. Public health would be improved by raising awareness of wildfire smoke exposure for high-risk subpopulations. Other efforts, such as prescribed fires, can reduce "the intensity, size, and damage of wildfires" (20, p. 117), which may benefit high-risk communities.

The patterns of subpopulations with higher exposure to smoke waves relate to the patterns of wildfire smoke and the interacting patterns of race, poverty, urbanicity, and region. Persons who are ethnic minorities are more likely to be socioeconomically disadvantaged (21). Poverty and education have been used as a indicators of SES in previous studies in which the associations between air pollution and health were investigated (22–25). Our findings suggest that counties with low SES might be more likely than others to experience intense smoke waves. These findings are generally consistent with conclusions from previous studies on SES and air pollution (26–28).

Although our results relate to the ambient levels of $PM_{2.5}$ due to wildfires, personal exposures may also differ by subpopulation. Persons with disadvantaged SES might be less aware of the potential health risks caused by wildfire smoke (29) or less likely to quickly respond to extreme wildfire smoke by moving or staying indoors (30). They are also more likely to live in low-cost neighborhoods that lack community support in response to adverse environmental conditions (28). All of these could result in higher exposures to wildfire smoke.

Some subpopulations might be more vulnerable in health response to wildfire-specific $PM_{2.5}$ because of biological and/or social factors. Results from the literature have suggested that females might be more vulnerable than males, possibly because of differences in lung function and dermal absorption (11). In the present study, the central estimate of the smoke-wave association was higher for women than for men, but those for

Table 2. Percent Change in Rate of Respiratory Hospital Admissions on Smoke-Wave Days Compared With Non–Smoke-Wave Days, by Subpopulation, Western US Counties, 2004–2009

Subpopulation	Relative Risk of Hospital Admission[a]		Difference in % Change in Rates of Admission[b]	
	Central Estimate	95% CI	Central Estimate	95% CI
Age, years[c]				
65–74	1.07	0.97, 1.18	0.0	Referent
75–84	1.08	0.99, 1.18	0.9	−10.0, 13.2
>85	1.06	0.97, 1.17	−0.5	−11.8, 12.2
Sex[c]				
Male	1.04	0.95, 1.13	0.0	Referent
Female	1.10	1.02, 1.20[d]	6.5	−3.2, 17.1
Race[c]				
White	1.07	1.00[e], 1.15	0.0	Referent
Black	1.22	1.00, 1.47[d]	13.8	−6.0, 37.9
Other race	1.04	0.90, 1.18	−3.2	−15.5, 10.9
Urbanicity[f]				
Urban	1.07	0.99, 1.15	0.0	Referent
Less urban and rural	1.12	0.96, 1.29	4.8	−11.2, 23.5
Region[f]				
California	1.04	0.96, 1.12	0.0	Referent
Northwest	1.28	0.98, 1.67	23.6	−6.3, 63.0
Southwest	1.09	0.51, 2.38	5.5	−51.7, 130.5
Rocky Mountains	1.04	0.73, 1.47	0.5	−29.4, 43.0
Poverty, %[f]				
<10	1.23	0.86, 1.76	0.0	Referent
10–15	1.06	0.93, 1.20	−14.4	−41.5, 25.3
>15	1.06	0.98, 1.15	−14.0	−40.4, 24.1
Educational level[f]				
≥20% with bachelor's degree	1.06	0.98, 1.14	0.0	Referent
<20% with bachelor's degree	1.13	0.97, 1.31	6.3	−10.2, 25.8

Abbreviation: CI, confidence interval.

[a] Relative risk of hospital admission for respiratory causes on smoke-wave days compared with non–smoke-wave days within subpopulation.

[b] Difference in percent change in rates of admission on smoke-wave days compared with non–smoke-wave days when comparing rates in subpopulation with rates in the reference population.

[c] Associations for individual-level characteristics were estimated using interaction models.

[d] Statistically significant difference between the subpopulation and reference subpopulation ($P < 0.05$).

[e] The lower confidence interval is 0.996 and was rounded to 1.00.

[f] Associations for community-level characteristics were estimated using stratified models.

the 2 sexes were not statistically different. Results from previous studies also suggested that those with lower SES may have higher health risks because of poorer nutrition, less access to health care (31), and higher baseline health rates (e.g., a higher morbidity rate than other subpopulations) (Web Table 1). We found that central estimates of smoke-wave associations for persons in less-educated counties were higher than those for persons in more-educated counties, but the associations for the 2 educational levels were not statistically different.

More studies are needed to investigate the association between exposure to wildfire smoke and health outcomes, especially among vulnerable populations (3). In some prior work, researchers investigated wildfire vulnerability. Künzli et al. (32) assessed exposure to wildfire smoke by surveying the number of days participants smelled smoke. Their findings suggested higher exposure for elementary school children than for high school children. Some prior studies indicated that, in general, older people (e.g., >65 years of age) (5–7, 9) and small children (0–4 years of age) are the most vulnerable to wildfire smoke (6). Some studies found low SES populations to be more vulnerable than other populations (33–37). Two studies found females to be more vulnerable than males to wildfire smoke (35, 37). In most earlier studies, researchers defined wildfire periods or seasons a priori and assessed health risks in relation

to variations of metrics of total mass air pollutant levels potentially elevated by wildfire smoke, whereas we assessed exposure to $PM_{2.5}$ specifically from wildfire smoke.

The subpopulations that experience higher exposure to wildfire-specific $PM_{2.5}$ may be similar to those subpopulations with higher exposures to all-source $PM_{2.5}$ (i.e., total mass $PM_{2.5}$). In the United States, persons who are black, have a low educational level (less than a high school diploma), and live in poverty have higher exposure to ambient $PM_{2.5}$ (26).

The subpopulations that are vulnerable to potential health effects from wildfire-specific $PM_{2.5}$ may differ from those who are vulnerable to all-source $PM_{2.5}$. The association between total mass $PM_{2.5}$ concentrations and hospital admissions for respiratory conditions among Medicare patients (≥65 years of age) was higher in northern California and the Rocky Mountain regions than the rest of the western United States (38). In comparison, we found that the central estimate of smoke waves for persons older than 65 years in the northwestern region of the United States was higher than that for persons from other western regions of the United States, but risks were not significantly different across regions. Bell et al. (39) found that women were more vulnerable than were men to hospital admissions associated with all-source $PM_{2.5}$ concentrations. People older than 75 years of age had higher risks for admissions due to chronic obstructive pulmonary disease when exposed to total mass $PM_{2.5}$ than did people aged 65–74 years (40), but we did not find differences in association estimates by age for wildfire-specific $PM_{2.5}$.

In the present study, we assessed vulnerability based on a large spatial domain and 6-year period with numerous wildfire smoke episodes. Our results provide suggestive evidence that sex, sociodemographic characteristics, and region may play a role in vulnerability to wildfire smoke. More research is needed to estimate vulnerability to wildfire smoke by incorporating future wildfire patterns and changes in demographic characteristics.

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Author affiliations: School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut (Jia Coco Liu, Keita Ebisu, Michelle L. Bell); Department of Biostatistics, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, Maryland (Jia Coco Liu, Roger D. Peng); Department of Biostatistics, T.H. Chan School of Public Health, Harvard University, Boston, Massachusetts (Ander Wilson, Yun Wang, Francesca Dominici); and Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts (Loretta J. Mickley, Melissa P. Sulprizio, Xu Yue).

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