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ORIGINAL RESEARCH

Wildfire Air Pollution and Rates of Cardiovascular Events and Mortality in Northern California in 2018

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BACKGROUND: We examined the association between acute cardiovascular disease (CVD) events and wildfire air pollution in California in 2018.

METHODS: The study included adult (≥18 years) members of Kaiser Permanente Northern California, an integrated health care system. Outcomes included CVD events (hospitalizations for acute myocardial infarction, heart failure, or stroke, and CVD death) and death from any cause. Fine particulate air pollution (particulate matter <2.5 microns in diameter; $PM_{2.5}$) exposure was assessed in categories (Good <12 $\mu g/m^3$, Moderate 12–34 $\mu g/m^3$, High ≥35 $\mu g/m^3$) and continuously. Poisson time series regression was used to model daily event rates during July 1 to December 31, 2018, using a spline to adjust for long-term time trends. We calculated rate ratios (RR) to estimate the association between wildfire air pollution and daily rate of CVD events and deaths.

RESULTS: Our study included 3.2 million adults with a total follow-up of 587.9 million person-days. High $PM_{2.5}$ concentrations during the Mendocino Complex wildfire in July to August was associated with an increased rate of CVD events (RR, 1.231 [95% CI, 1.039–1.458]) and death (RR, 1.358 [95% CI, 1.128–1.635]) compared with Good $PM_{2.5}$ concentrations. In contrast, there was no evidence of increased risk during the Camp wildfire in November (RR for CVD events, 0.966 [95% CI, 0.894–1.044]; RR for all-cause mortality, 0.985 [95% CI, 0.904–1.074] High versus Good $PM_{2.5}$ concentrations).

CONCLUSIONS: There was some evidence of increased rates of CVD events and death during wildfires, but results were inconsistent. With ongoing climate change, large wildfires are a pressing public health concern and future work is needed to understand differences in health outcomes by wildfire.

Key Words: myocardial infarction ■ particulate matter ■ wildfire ■ wildfire smoke ■ wildland fire

Wildfires are increasingly frequent, with climate change contributing to worsening duration and intensity of wildfires.[1] Smoke from large wildfires can spread hundreds of miles, affecting air quality for millions of people.[2] Wildfire smoke increases air pollution, often resulting in concentrations of fine particulate matter <2.5 microns in diameter ($PM_{2.5}$), that exceed the Environmental Protection Agency's (EPA's) 24-hour National Ambient Air Quality Standard of 35 $\mu g/m^3$.[3,4] Therefore, understanding the effects of wildfire-related air pollution is a pressing public health concern.

$PM_{2.5}$ air pollution exposure has been strongly associated with cardiovascular health outcomes,[5,6] and both the American Heart Association and the EPA have concluded that the scientific evidence is consistent with a causal relationship.[7] However, the association of wildfire-related $PM_{2.5}$ with cardiovascular health outcomes has been inconsistent.[8,9] Review papers found

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CLINICAL PERSPECTIVE

What Is New?

- We found increased rates of cardiovascular events and death associated with high air pollution during the 2018 Mendocino Complex wildfire but not during the Camp wildfire.
- At typical exposure levels, higher air pollution was associated with increased rates of cardiovascular events and death.

What Are the Clinical Implications?

- Particulate air pollution, which comes from wildfires and routine emissions, is a risk factor for cardiovascular events and death.
- Policy measures and individual protective actions may be needed to reduce patients' exposure to air pollution and prevent cardiovascular events.

Nonstandard Abbreviations and Acronyms

EPA	Environmental Protection Agency
PM	particulate matter
$PM_{2.5}$	particulate matter <2.5 microns in diameter

mixed results across prior studies and concluded that the strength of evidence for wildfire PM was "inconclusive" for cardiovascular outcomes.[8,9] One knowledge gap identified was whether increasing public awareness may change behavior, which could reduce levels of exposure and mitigate adverse health impacts.[8]

The 2018 wildfire season in California was the worst on record at the time. The Mendocino Complex and other fires (July–August) and the Camp fire (November) each burned more than 100 000 acres and spread smoke plumes across Northern California.[10] We examined the associations of wildfire air pollution with acute cardiovascular disease events and deaths during 2018 in California. Our study examined associations of wildfire air pollution with acute cardiovascular disease (CVD) events and deaths during 2018, focusing on these 2 major wildfires. In post hoc analyses, we analyzed Google search trends for terms related to air quality and personal protections to understand public awareness during these major wildfires.

METHODS

Study Population

Our study included adult (age≥18) members of Kaiser Permanente Northern California (KPNC), an integrated health care system, who lived in a 35-county region. The KPNC integrated health care system includes a nonprofit health insurance plan and a system of nonprofit hospitals and outpatient clinics. KPNC insures approximately one third of the population in the region, and the members are generally very representative of the underlying population.[11] Patient address data, including geocoded address locations, were extracted from electronic health record databases. All adults who were KPNC members at the study start on July 1, 2018 and had a geocoded patient address in the 35-county region were included. Of the 3 331 731 adults who were KPNC members on July 1, 2018, only 1.26% were excluded from the study (20 733 [0.62%] had an address outside of the 35-county study region and 21 159 [0.64%] had an address that could not be geocoded).

The study was approved by the Kaiser Foundation Research Institute's Institutional Review Board and informed consent was waived because the study uses retrospective data only with no participant contact. These data contain protected health information and are available to researchers only through approval by the Kaiser Foundation Research Institute's Institutional Review Board. Requests to access the data set from qualified researchers trained in human subject confidentiality protocols may be sent to the corresponding author.

Outcomes

Using electronic health records, we derived data on 2 outcomes: any CVD event and death from any cause. Any CVD event was defined as a combined end point including hospitalizations for acute myocardial infarction, heart failure, or stroke as well as CVD death using the *International Classification of Diseases, Tenth Revision, Clinical Modification* (*ICD-10-CM*) codes. Acute myocardial infarction was defined as an inpatient principal discharge diagnosis of *ICD-10-CM* codes I21.x and I22.x.[12] Stroke was defined as an inpatient principal discharge diagnosis or emergency department principal discharge diagnosis of *ICD-10-CM* codes I60.9, I61.x-I63.x.[12] Heart failure was defined as an inpatient principal discharge diagnosis of *ICD-10-CM* codes I50.x, I11.0, I13.0, I13.2, I97.13, I97.130, I97.131, and I09.81.[12] The date of hospitalization was based on the date of admission.

Air Pollution and Smoke Plumes

Daily 24-hour mean $PM_{2.5}$ concentrations were obtained from EPA Air Quality System monitors, with 90 $PM_{2.5}$ monitors in operation in the study region during 2018.[13] Daily $PM_{2.5}$ concentrations at patient addresses were generated using thin plate splines for spatial data.[14] The thin plate spline model had excellent performance, with R^2=0.80 in leave-one-out-cross-validation of monitors. Daily smoke plume data were

obtained from the National Oceanic and Atmospheric Administration Hazard Mapping System fire and smoke database to determine areas affected by wildfire smoke.[15] Wildfire $PM_{2.5}$ was $PM_{2.5}$ with the presence of a smoke plume and nonwildfire $PM_{2.5}$ was $PM_{2.5}$ without the presence of a smoke plume.

Statistical Analysis

Poisson time series regression was used to model daily event rates from July 1 to December 31, 2018. Following established methods for air pollution time series, models included adjustment for weekday effects and a spline to adjust for long-term time trends. Models accounted for overdispersion by using the quasi-Poisson distribution (details in Data S1).[16,17] Associations between air pollution and CVD outcomes were estimated as rate ratios (RR) and 95% CIs. $PM_{2.5}$ concentrations were categorized as Good (<12 $\mu g/m^3$), Moderate (12–34 $\mu g/m^3$), and High (≥35 $\mu g/m^3$) based on EPA air quality index categories in effect during the time of the study in 2018, with concentrations in the High category exceeding the EPA regulation limit set to protect public health.[18] In sensitivity analyses, we used the EPA's recently updated cutpoints for Good (<9 $\mu g/m^3$) and Moderate (9–34 $\mu g/m^3$), noting that the EPA kept the same cutpoint for High (≥35 $\mu g/m^3$).[19] Another sensitivity analysis restricted the Good and Moderate $PM_{2.5}$ categories to exclude days during major wildfires when there were High $PM_{2.5}$ concentrations in other locations within the study area. Additional sensitivity analyses examined wildfire smoke within $PM_{2.5}$ categories below the EPA limit and also examined lagged associations for lags of 1 to 6 days. In secondary analyses, we estimated the RR for the linear association of continuous $PM_{2.5}$ and assessed whether the slope of the association changed during each wildfire using segmented regression. We assessed nonlinearity of associations using splines.

Post Hoc Analyses

In post hoc analyses, we explored public awareness by examining Google Trends search scores for terms "wildfire smoke," "air quality," and "N95 mask." Google Trends search scores were obtained from Google Trends.[20] Google Trends search scores are standardized to a range of 0 to 100 and reflect relative search interest over time.[21] We examined weekly Google Trends search scores for each search term within California and within metropolitan areas in our study region during 2018.

RESULTS

Table 1 shows the study sample characteristics of the 3 289 839 adults in the study. The study sample was 52% female, 48% male, with mean age 47 years (SD 18 years). The sample was very diverse: 20% Asian, 7% Black, 18% Hispanic White, 45% White, <1% American Indian/Alaska Native, 4% multiple races, and 6% missing. The study included a total of 587.9 million person-days during July 1, 2018 through December 31, 2018.

Table 1. Characteristics of Study Sample of Kaiser Permanente Members in Northern and Central California in 2018

Characteristic	No.	%
Sex		
Female	1 709 750	51.97
Male	1 579 879	48.02
Missing	210	0.01
Age, y		
Age, mean±SD	47.28	17.86
Race or ethnicity		
White, non-Hispanic	1 476 274	44.87
Hispanic White	606 916	18.45
Black	219 344	6.67
American Indian/Alaska Native	15 812	0.48
Asian/Pacific Islander	666 053	20.25
Multiple races	132 890	4.04
Missing	172 550	5.24
Neighborhood education*		
<5% (high SES)	828 528	27.92
5% to <10%	918 569	25.18
10% to <20%	918 160	27.91
20% or more (low SES)	624 576	18.99
Missing	6	<0.01
Smoking		
Never	1 981 419	60.23
Former	705 265	21.44
Current	381 916	11.61
Missing	221 239	6.72

SES indicates socioeconomic status.
*Census tract level percent of adults with less than a high school education.

The Mendocino Complex and other fires (July–August) and the Camp fire (November) each burned more than 100 000 acres and spread smoke plumes across Northern California. These smoke plumes stretched hundreds of miles across the study region (Figure 1). The Mendocino Complex and other fires were actively burning for almost 2 months, with smoke in the air for 26 to 51 days depending on the county (Table S1). The Camp fire was contained more quickly, with smoke in the air for 11 to 15 days depending on the county (Table S1). During both fires, $PM_{2.5}$ concentrations exceeded the EPA daily limit of 35 $\mu g/m^3$, whereas $PM_{2.5}$ exposure was typically below the limit on days unaffected by these large wildfires (Figure 2).

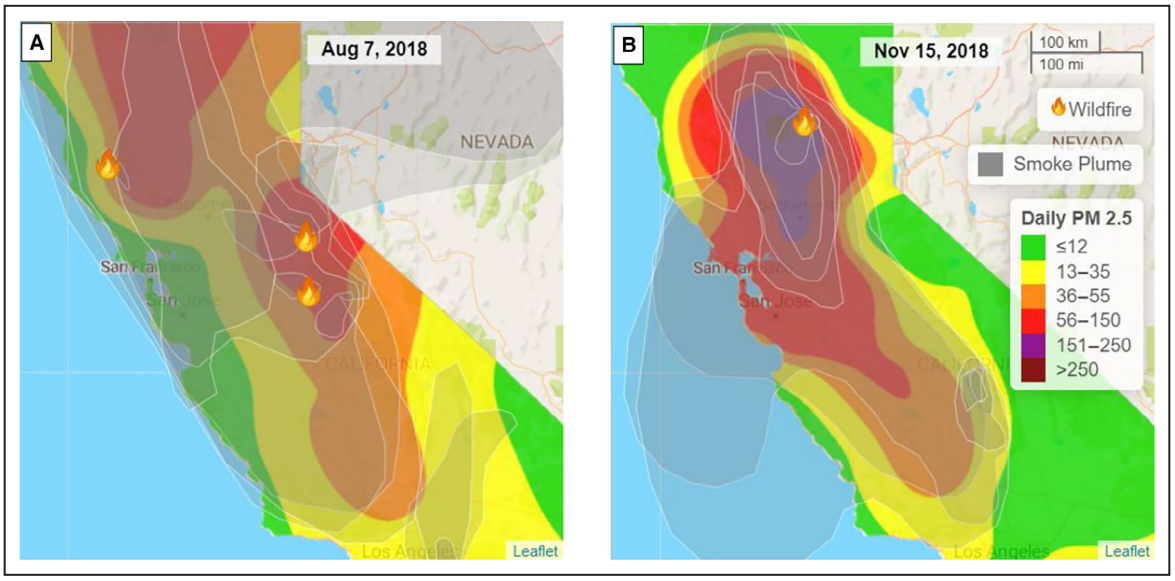

Figure 1. $PM_{2.5}$ air pollution concentrations and smoke plumes during 2018 wildfires: Mendocino Complex and other fires (A), Camp fire (B).
$PM_{2.5}$ indicates particulate matter <2.5 microns in diameter.

In our study of 3.2 million adults, the Mendocino Complex and other fires resulted in High $PM_{2.5}$ (above the EPA daily limit of 35 $\mu g/m^3$) for 4.7 million person-days (1%). The Camp fire resulted in High $PM_{2.5}$ for 35.9 million person-days (6%), with $PM_{2.5}$ concentrations reaching the highest concentrations in the world on some days.[22] In contrast, $PM_{2.5}$ concentrations rarely reached the High category on other days in the study period (<1000 person-days, <0.1%). $PM_{2.5}$ concentrations were in the EPA's Good category on most days (390.7 million person-days, 66%) and in the Moderate category on many other days (156.5 million person-days, 27%). With thousands of other wildfires in California 2018, smaller smoke plumes were present on many other days.[10] Of the 156.5 million person-days of exposure in the Moderate category, smoke was present for 73.0 million person-days (47%). Of the 390.7 million person-days of exposure in the Good catgegory, smoke was present for 78.5 million person-days (20%).

High $PM_{2.5}$ during the summer Mendocino Complex and other fires was associated with a 23.1% increased rate of CVD events (RR, 1.231 [95% CI, 1.039–1.458]) and a 35.8% increased rate of all-cause mortality (RR, 1.358 [95% CI, 1.128–1.635]) compared with Good $PM_{2.5}$ concentrations (Table 2). In contrast, there was

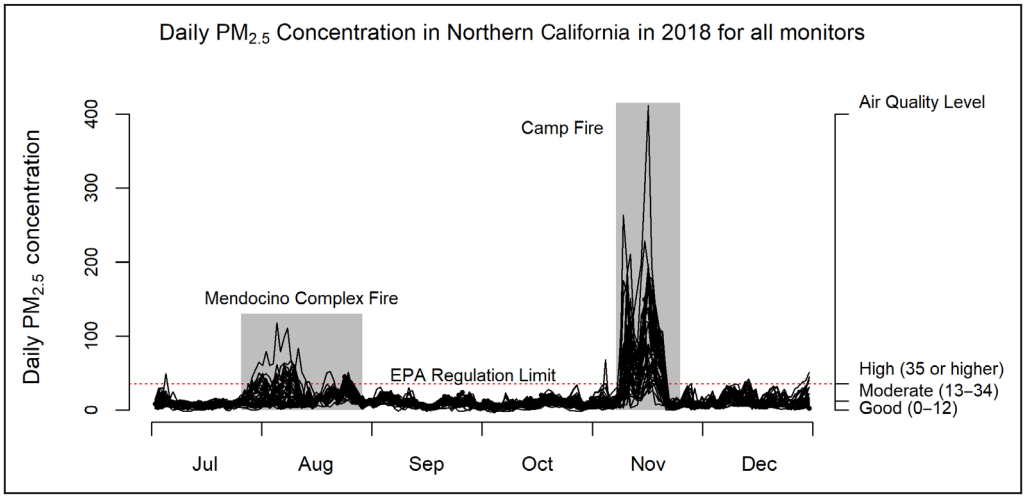

Figure 2. Daily concentrations of $PM_{2.5}$ at air pollution monitors in Northern and Central California during July–December 2018.
EPA indicates Environmental Protection Agency; and $PM_{2.5}$, particulate matter <2.5 microns in diameter.

Table 2. Associations of $PM_{2.5}$ With CVD Events and All-Cause Mortality During 2018 in Northern and Central California for Moderate $PM_{2.5}$ and High $PM_{2.5}$ During 2 Major Wildfires

$PM_{2.5}$ exposure	CVD events		All-cause mortality	
	RR	(95% CI)	RR	(95% CI)
$PM_{2.5}$ categories				
Good	1.000	(ref)	1.000	(ref)
Moderate	1.022	(0.982–1.063)	1.043	(0.998–1.090)
High—Mendocino Complex fire	1.231	(1.039–1.458)	1.358	(1.128–1.635)
High—Camp fire	0.966	(0.894–1.044)	0.985	(0.904–1.074)

CVD indicates cardiovascular disease; $PM_{2.5}$, particulate matter <2.5 microns in diameter; and RR, rate ratio.

no evidence of increased risk from High $PM_{2.5}$ during the later Camp fire (RR for CVD events, 0.966 [95% CI, 0.894–1.044]; RR for all-cause mortality, 0.985 [95% CI, 0.904–1.074]) compared with Good $PM_{2.5}$ concentrations. Moderate $PM_{2.5}$ concentrations had no association with CVD events (1.022 [95% CI, 0.982–1.063]) and a suggestive association with all-cause mortality (1.043 [95% CI, 0.998–1.090]) compared with Good $PM_{2.5}$ concentrations (Table 2). Associations were similar in sensitivity analyses changing the Good and Moderate categories (Tables S2 and S3). The association of Moderate versus Good $PM_{2.5}$ concentrations was similar for wildfire $PM_{2.5}$ and nonwildfire $PM_{2.5}$ in categorical analyses (Table S4). The sensitivity analysis of different lags found the strongest associations for the same day of exposure and also showed strong associations 4 days after exposure (Table S5).

Results for continuous analyses of $PM_{2.5}$ below the EPA daily limit are shown in Figure 3 and Table S6. We found a 4.1% increased rate of all-cause mortality (RR, 1.041 [95% CI, 1.004–1.080]) per 10 $\mu g/m^3$ increase in overall daily $PM_{2.5}$. Associations with all-cause mortality were extremely similar for wildfire $PM_{2.5}$ (RR, 1.042 [95% CI, 1.001–1.084]) and nonwildfire $PM_{2.5}$ (RR, 1.040 [95% CI, 0.996–1.086]; *P*-value for interaction 0.9473). We found a 4.8% increased rate of CVD events (RR, 1.048 [95% CI, 1.015–1.082]) per 10 $\mu g/m^3$ increase in overall daily $PM_{2.5}$. The association with CVD events was slightly larger for nonwildfire $PM_{2.5}$ (RR, 1.074 [95% CI, 1.035–1.114]) than for wildfire $PM_{2.5}$ (RR, 1.032 [95% CI, 0.996–1.068]), and there was a statistically significant difference between the associations (*P* value for interaction 0.0241). Linear associations did not differ when $PM_{2.5}$ was high (above the EPA limit of 35 $\mu g/m^3$)

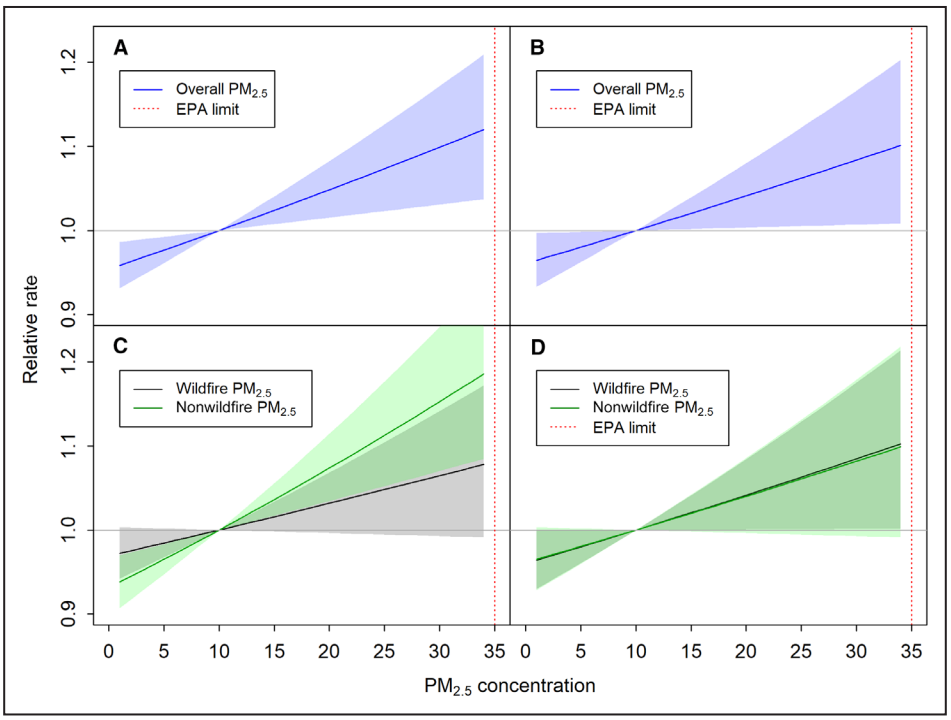

Figure 3. Associations of $PM_{2.5}$ with CVD events and all-cause mortality during 2018 in Northern and Central California, for $PM_{2.5}$ concentrations below the EPA limit of 35 $\mu g/m^3$, overall and by wildfire and nonwildfire $PM_{2.5}$.
A, overall $PM_{2.5}$ and CVD events, (**B**) overall $PM_{2.5}$ and all-cause mortality, (**C**) wildfire $PM_{2.5}$, nonwildfire $PM_{2.5}$ and CVD events, (**D**) wildfire $PM_{2.5}$, nonwildfire $PM_{2.5}$ and all-cause mortality. CVD indicates cardiovascular disease; EPA, Environmental Protection Agency; and $PM_{2.5}$, particulate matter <2.5 microns in diameter.

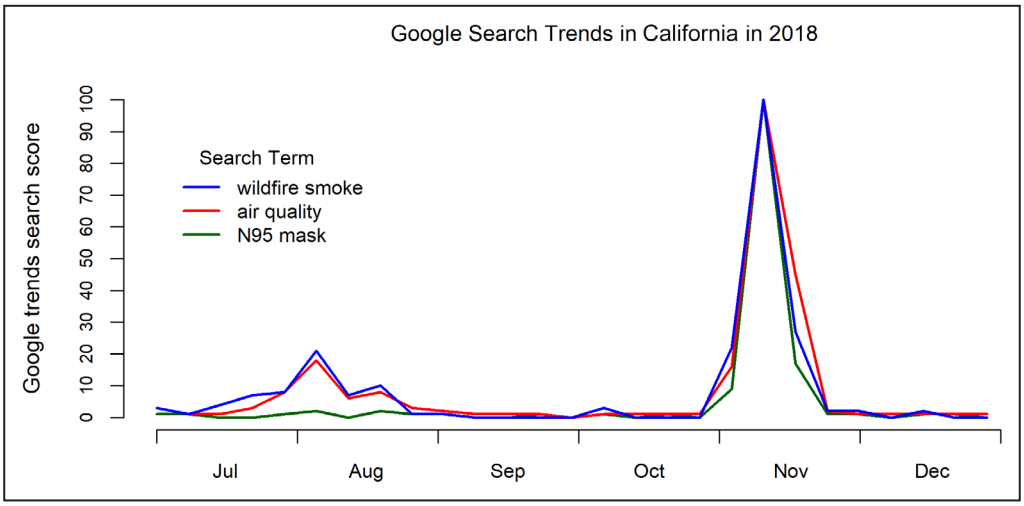

Figure 4. Google Trends scores for wildfire related search terms in California during July to December 2018.

during the Mendocino Complex and other fires (*P* values for interaction 0.675–0.222). The linear associations differed during the Camp fire when $PM_{2.5}$ was high, with no evidence of an increased rate for CVD events (RR, 0.985 [95% CI, 0.970–1.002], *P* value for interaction 0.001) or all-cause mortality (RR, 0.986 [95% CI, 0.968–1.004]; *P* value for interaction 0.012) per 10 $\mu g/m^3$ increase in daily $PM_{2.5}$.

Analyses of potential nonlinearity were consistent with the main analyses. We found increasing trends in $PM_{2.5}$ associations within the typical exposure range <35 $\mu g/m^3$ with decreases to a null association at higher exposures (Figure S1). When splines were refit excluding the Camp fire days by using a separate term for those exposures, the overall $PM_{2.5}$ showed an increasing trend, including in the high exposure range (Figure S2). Thus, high $PM_{2.5}$ exposures during the Camp fire days appear to have null associations, similar to our main analyses.

During the Camp fire on Thursday, November 16, 2018, Google reported that searches for smoke masks were at the highest level in Google's history.[22] Post hoc analyses of Google Trends search scores are shown in Figure 4. We found that search terms reached maximum interest during the Camp fire (scores of 100), whereas search interest was much lower during the Mendocino Complex and other fires (scores 1–24), and very low in days unaffected by these wildfires (scores 0–3). The only exception was in Chico-Redding, which had high scores for searching "air quality" during both fires. We emphasize these were exploratory post hoc analyses.

DISCUSSION

Our results showed evidence of increased risk of cardiovascular events and death associated with high $PM_{2.5}$ during the Mendocino Complex and other fires but not during the Camp fire. In continuous analyses of $PM_{2.5}$ below the EPA daily limit, $PM_{2.5}$ was associated with increased rates of cardiovascular events and death. Wildfire-$PM_{2.5}$ and nonwildfire $PM_{2.5}$ had very similar associations with all-cause mortality, and the association with CVD events was slightly larger for nonwildfire $PM_{2.5}$ than for wildfire $PM_{2.5}$. Our findings are generally consistent with prior studies, which have found mixed results for the association between wildfire air pollution and cardiovascular mortality.

Recent review papers evaluating prior studies of wildfire PM and cardiovascular outcomes found that results have been inconsistent across studies and concluded that the strength of evidence was inconclusive for cardiovascular outcomes.[8,9] A study of the 2008 Northern California wildfires found no evidence of an increased rate of cardiovascular hospital admissions (RR, 0.995 [95% CI, 0.988–1.002] per 5 $\mu g/m^3$ change in $PM_{2.5}$ during wildfires) but did find a small increased rate of respiratory hospital admissions (RR, 1.015 [95% CI, 1.009–1.020]) per 5 $\mu g/m^3$ change in $PM_{2.5}$ during wildfires.[23] Similarly, a study of Colorado wildfires also found no evidence of an increased rate of cardiovascular hospital admissions but did find an increased rate of respiratory hospital admissions.[24]

Our findings for the continuous analyses of overall $PM_{2.5}$ are consistent with previous multicity studies and meta-analyses, which have found relative increases of 1.007 (95% CI, 1.006–1.008), 1.011 (95% CI, 1.010–1.012), and 1.010 (95% CI, 1.005–1.016) for daily mortality per 10 $\mu g/m^3$ increase in short-term exposures to $PM_{2.5}$, with steeper slopes at lower concentrations.[25–27] A recent study of wildfire-related $PM_{2.5}$ exposure found similar RR: 1.019 (95% CI, 1.016–1.022) for all-cause mortality and 1.017 (95% CI, 1.012–1.021) for

cardiovascular mortality associated with each 10 μg/m^3 increase in short-term wildfire-related $PM_{2.5}$.[28] Most of the wildfire-related $PM_{2.5}$ exposure in that study was in the more typical exposure range < 60 μg/m^3, which is more similar to the Mendocino complex fire in our study and lower than the extreme concentrations during the Camp fire. Our findings are also consistent with a recent study of wildfire smoke and all-cause ED visits, which found increased rates of ED visits associated with low or moderate intensity wildfire smoke but decreased rates associated with heavy smoke.[29]

One knowledge gap identified in prior reviews was whether increasing awareness may limit exposure and mitigate adverse health impacts.[8] During the Camp fire, many schools were closed, outdoor events were canceled, and health officials urged residents to stay indoors or wear N95 masks when they could not avoid leaving their homes.[22,30] The analysis of Google Trends search scores was conducted post hoc as a way of exploring our unexpected study findings for the 2 major wildfires in 2018. These descriptive findings should be considered exploratory and hypothesis generating. Our findings are consistent with a recent study that found that increased wildfire smoke was associated with several behavioral changes including an increase in popularity for air-quality-related search terms and an increase in the proportion of people who stayed fully at home (based on cell phone data).[31] Future work is needed to rigorously quantify the degree of public health interventions (canceling events, messaging to stay indoors) and personal interventions (wearing an N95 mask, closing windows, using an in-home air purifier) during wildfires.

An alternative explanation for the differences in results for the Mendocino Complex fire and the Camp fire relates to the timing of the 2 fires. There is a phenomenon in the air pollution literature referred as "harvesting," "displacement," or "depletion of the susceptibles," which is when the people who are most at risk of the outcome experience the outcome in response to the first high exposure and are subsequently either ineligible or less likely to have the outcome in response to the next high exposure.[32] This displacement may occur on the scale of months or days. Depletion of the susceptibles can bias later estimates toward the null.[33,34] Because the Mendocino complex fire occurred a few months before the Camp fire, it is possible that exposure to high $PM_{2.5}$ during the Mendocino fire triggered cardiovascular events and death in individuals who were on the verge of having an event and could have caused a temporary deficit in the population of people who were at risk of acute cardiovascular events during the Camp fire.

Our study has several strengths and limitations. Our population of Kaiser members is large, diverse, and representative of the Northern California region. Our approach for modeling daily $PM_{2.5}$ concentrations had excellent performance, with R^2=0.80. Recent studies using machine learning approaches to model $PM_{2.5}$ have reported R^2 of 0.66 to 0.78 in validation and have found underprediction of high values of $PM_{2.5}$ during wildfires.[35,36] A limitation of this study is that we do not have data on individuals' activity patterns or time spent outdoors during the fires. We also do not have data on the percentage of residents who traveled to other parts of the state during the Camp fire or the Mendocino Complex wildfire; some people may have traveled to higher exposure areas for work or other obligations, while others may have traveled to lower exposure areas. In addition, despite the large sample size, our study did not have enough power to enable subgroup comparisons because the total person-time exposure for High $PM_{2.5}$ during these major wildfires was a relatively small proportion of the total person-time exposures.

Conclusions

Overall, we found some evidence of increased risk of cardiovascular events and death associated with wildfire air pollution. Our mixed results for the 2 major 2018 wildfires are similar to prior literature showing inconsistent associations across studies. Future work is needed to formally examine how public health and individual protective actions may affect individuals' exposures and outcomes during wildfires. With ongoing climate change, large wildfires are a pressing public health concern and determining the underlying drivers of these mixed results remains an important research need.

ARTICLE INFORMATION

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Disclosures

None.

Supplemental Material

Data S1
Tables S1–S6
Figures S1–S2

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