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Wildfire Smoke Exposure and Incident Dementia

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IMPORTANCE Long-term exposure to total fine particulate matter ($PM_{2.5}$) is a recognized dementia risk factor, but less is known about wildfire-generated $PM_{2.5}$, an increasingly common $PM_{2.5}$ source.

OBJECTIVE To assess the association between long-term wildfire and nonwildfire $PM_{2.5}$ exposure and risk of incident dementia.

DESIGN, SETTING, AND PARTICIPANTS This open cohort study was conducted using January 2008 to December 2019 electronic health record (EHR) data among members of Kaiser Permanente Southern California (KPSC), which serves 4.7 million people across 10 California counties. KPSC members aged 60 years or older were eligible for inclusion. Members were excluded if they did not meet eligibility criteria, if they had a dementia diagnosis before cohort entry, or if EHR data lacked address information. Data analysis was conducted from May 2023 to May 2024.

EXPOSURES Three-year rolling mean wildfire and nonwildfire $PM_{2.5}$ in member census tracts from January 2006 to December 2019, updated quarterly and estimated via monitoring and remote-sensing data and statistical techniques.

MAIN OUTCOME AND MEASURES The primary outcome was incident dementia, identified using diagnostic codes in the EHR. Odds of dementia diagnoses associated with 3-year mean wildfire and nonwildfire $PM_{2.5}$ exposure were estimated using a discrete-time approach with pooled logistic regression. Models adjusted for age, sex, race and ethnicity (considered as a social construct rather than as a biological determinant), marital status, smoking status, calendar year, and census tract–level poverty and population density. Stratified models assessed effect measure modification by age, sex, race and ethnicity, and census tract–level poverty.

RESULTS Among 1.64 million KPSC members aged 60 years or older during the study period, 1 223 107 members were eligible for inclusion in this study. The study population consisted of 644 766 female members (53.0%). In total, 319 521 members identified as Hispanic (26.0%), 601 334 members identified as non-Hispanic White (49.0%), and 80 993 members received a dementia diagnosis during follow-up (6.6%). In adjusted models, a 1-$\mu g/m^3$ increase in the 3-year mean of wildfire $PM_{2.5}$ exposure was associated with an 18% increase in the odds of dementia diagnosis (odds ratio [OR], 1.18; 95% CI, 1.03-1.34). In comparison, a 1-$\mu g/m^3$ increase in nonwildfire $PM_{2.5}$ exposure was associated with a 1% increase (OR, 1.01; 95% CI, 1.01-1.02). For wildfire $PM_{2.5}$ exposure, associations were stronger among members less than 75 years old upon cohort entry, members from racially minoritized subgroups, and those living in high-poverty vs low-poverty census tracts.

CONCLUSIONS AND RELEVANCE In this cohort study, after adjusting for measured confounders, long-term exposure to wildfire and nonwildfire $PM_{2.5}$ over a 3-year period was associated with dementia diagnoses. As the climate changes, interventions focused on reducing wildfire $PM_{2.5}$ exposure may reduce dementia diagnoses and related inequities.

Supplemental content

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Wildfires, once rare and geographically confined, now regularly impact populations across the US.[1] Anthropogenic climate change has increased wildfire frequency and intensity, eroding gains in air quality achieved under the Clean Air Act in the Western US.[2-5] Today, wildfire-generated fine particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) accounts for over 70% of total $PM_{2.5}$ exposure on poor air-quality days in California,[6] where the 2018 wildfire season alone resulted in an estimated $149 billion in capital, health, and economic damages.[7]

Prior research suggests long-term exposure to $PM_{2.5}$, a major health-harmful component of wildfire smoke,[8-10] is associated with incident dementia,[11] with a strong biological basis for the observed association.[12-14] Exposure to $PM_{2.5}$ may accelerate neurodegenerative processes through enhanced production of reactive oxygen species,[15,16] altered blood-brain barrier permeability,[17-19] and overactivation of microglia, leading to excess production of cytotoxic factors.[12,20,21] Proposed routes of entry of $PM_{2.5}$ into the central nervous system include direct translocation via the olfactory nerve[20,22] and via peripheral circulation across the blood-brain barrier.[17,23,24] Exposure to $PM_{2.5}$ may indirectly increase dementia risk through prothrombotic physiologic changes leading to cerebrovascular dysfunction and stroke,[25-30] which may underlie some dementia diagnoses. Although wildfires have become a dominant $PM_{2.5}$ source in California, whether long-term exposure to wildfire $PM_{2.5}$ confers similar dementia risk remains uncertain despite differences in chemical compositions, oxidative potential, and size fractions.[31-33]

Motivated by the intensification of wildfire events in the US and globally, we examined the association of long-term wildfire and nonwildfire $PM_{2.5}$ exposure with incident dementia among older adults in Southern California. Our analysis leveraged detailed, longitudinal electronic health record (EHR) data with more than 10 years of longitudinal follow-up. This analysis explicitly considers key individual-level and community-level vulnerability factors that may impact long-term $PM_{2.5}$ exposure or the magnitude of an individual's health response.

Key Points

Question Is long-term exposure to wildfire smoke associated with incident dementia diagnosis?

Findings In this open cohort study of more than 1.2 million Kaiser Permanente Southern California members, long-term exposure to wildfire and nonwildfire fine particulate matter ($PM_{2.5}$) was associated with dementia diagnosis, with stronger associations observed in potentially vulnerable subgroups.

Meaning As climate change intensifies, interventions that reduce wildfire $PM_{2.5}$ exposure can potentially reduce the risk of dementia and support health equity.

Methods

This open cohort study used EHR data spanning from January 2008 to December 2019 from Kaiser Permanente Southern California (KPSC), a managed care consortium, with integration of the health plan, hospitals, and physician medical groups, which serve more than 4.7 million individuals.[34] KPSC membership reflects the sociodemographic diversity of Southern California, with minor underrepresentation of individuals with extremely low income and individuals with high education.[35] The KPSC EHR catalogs longitudinal records of members' residential address, sociodemographic characteristics, and diagnoses across care settings. This study included all KPSC members aged 60 years or older enrolled continuously for at least 1 year (allowing 90-day enrollment gaps), enrolled for 1 day in the year following their baseline year, living in a KPSC census tract, and free from dementia at cohort entry (eFigure 1 in Supplement 1). Follow-up extended from the date of cohort entry on or after January 1, 2009, through the date of dementia diagnosis, death, loss-to-follow-up, or administrative censoring on December 31, 2019. Data analysis was conducted from May 2023 to May 2024.

This study was reported per the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines. Members with documentation requesting removal from all research studies were excluded. The study protocol was approved by the WCG institutional review board (IRB) and was also approved by the IRBs at KPSC, Columbia University, and the University of Washington. All IRBs waived the requirement for informed consent. Analyses were conducted using R version 4.3.2 (The R Foundation for Statistical Computing).

Wildfire Smoke Exposure

Daily mean concentrations of total $PM_{2.5}$ exposure were estimated for each Southern California census tract from 2006 to 2019 using an ensemble machine learning approach.[36] Predictor variables included outdoor $PM_{2.5}$ measurements from the Environmental Protection Agency Air Quality System, aerosol optical depth, plume height, meteorological variables (minimum and maximum temperature, specific humidity, wind speed and duration, precipitation, and surface shortwave radiation) extracted from the high-resolution Gridded Surface Meteorological dataset, and land use characteristics.[37] Daily concentrations of wildfire $PM_{2.5}$ were isolated from total $PM_{2.5}$ using the National Oceanic and Atmospheric Administration Hazard Mapping System (HMS), fire perimeter data from the California Department of Forestry and Fire Protection, and a spatiotemporal multiple imputation approach, as previously described.[36] Smoky tract-days were defined as days when an HMS smoke plume boundary intersected a given census tract. In brief, total $PM_{2.5}$ was first used to represent nonwildfire $PM_{2.5}$ concentrations on nonsmoky tract-days and then multiple imputation was used to estimate nonwildfire $PM_{2.5}$ concentrations on smoky tract-days. We subtracted the estimated nonwildfire $PM_{2.5}$ concentration from the total $PM_{2.5}$ concentration to obtain estimated wildfire $PM_{2.5}$ concentrations on smoky tract-days. Models achieved an R^2 value of 0.78 using hold-out test validation overall and when restricted to lower levels of wildfire $PM_{2.5}$ (ie, less than 50 $\mu g/m^3$).

As the relevant exposure period for air pollution remains unknown[38] and our wildfire $PM_{2.5}$ data extended from 2006 on, a 3-year mean exposure was selected. Using daily estimates, we calculated census tract–level wildfire and nonwildfire $PM_{2.5}$ concentrations as time-varying 3-year rolling means, updated quarterly. These estimates were linked to study participants based on their time-varying residential address geocoded to the census tract level.

Dementia Diagnosis

Dementia diagnoses from inpatient and outpatient visits between January 1, 2008, and December 31, 2019, were identified through the EHR using diagnostic codes from the *International Classification of Diseases, Ninth* and *Tenth Revision* (*ICD-9* and *ICD-10*).[39-42] The outcome comprises diagnoses of Alzheimer disease, Lewy body dementia, vascular dementia, and other dementias (eTable 1 in Supplement 1). Prior research suggests sensitivity of 77% and specificity of 95% for similar diagnostic codes used to identify all-cause dementia in EHR data compared with consensus dementia diagnosis.[43]

Covariates

EHR-derived member characteristics included age at cohort entry, sex (male or female), member-reported race and ethnicity (with categories including Hispanic, non-Hispanic Asian or Pacific Islander, non-Hispanic Black, non-Hispanic White, and other [multiple races, Native American and Alaskan Native, Pacific Islander, other, and unknown race and ethnicity]), smoking status (current, former, or never smoker), relationship status (married, domestic partner, common law marriage, divorced or separated, widowed, single, other, or unknown), and whether an interpreter was required at any health care encounters. The social constructs of race and ethnicity were included as covariates because these factors may stand in as a proxy for experiences of structural racism or social factors that may affect $PM_{2.5}$ exposure. Census tract–level covariates were obtained from the 2010 US Census and linked based on geocoded member addresses. These covariates included population density and percentage of the population living below the federal poverty threshold.[44] High-poverty census tracts were those in which 15% or more of the population lived below the federal poverty threshold. Tracts were otherwise classified as low poverty.

Statistical Analysis

A discrete-time approach with pooled logistic regression was used to estimate the odds of dementia diagnoses associated with a 1-$\mu g/m^3$ increase in the 3-year mean of wildfire $PM_{2.5}$ and nonwildfire $PM_{2.5}$ concentrations. In all models, we controlled for individual-level covariates identified a priori as potential confounders, including age (natural cubic spline with 2 degrees freedom), sex, race and ethnicity, smoking status, relationship status, and whether the member required an interpreter during health care encounters. Census tract–level covariates included population density and percentage living in poverty. All models additionally included fixed effects for calendar year to address potential secular trends in $PM_{2.5}$ levels and dementia diagnoses. Models did not control for vascular risk factors, such as hypertension or high cholesterol, because these factors likely mediate, rather than confound, the association between $PM_{2.5}$ exposure and dementia.[45-47] All *P* values were 2-sided, and statistical significance was set at $P = .05$.

Secondary Analyses

Alternative exposure metrics were considered that captured other facets of wildfire $PM_{2.5}$ exposure in their associations with dementia.[48] These included (1) each additional week where mean wildfire $PM_{2.5}$ concentrations exceeded 5 $\mu g/m^3$; (2) each IQR increase in the number of weeks wherein the mean wildfire $PM_{2.5}$ concentrations exceeded 0 $\mu g/m^3$; (3) each 10-$\mu g/m^3$ increase in the mean daily wildfire $PM_{2.5}$ concentration during the peak week of exposure; and (4) each additional smoke wave over a 3-year rolling exposure period. Smoke waves were defined as 2 or more consecutive days with a mean daily wildfire $PM_{2.5}$ concentration greater than 15 $\mu g/m^3$.[9] For comparability, we also estimated associations for an IQR increase in wildfire (approximately 0.1 $\mu g/m^3$) and nonwildfire $PM_{2.5}$ (approximately 3 $\mu g/m^3$). Because dementia risk and adverse responses to long-term $PM_{2.5}$ exposure may differ meaningfully by age,[49] sex,[50] race and ethnicity,[51] and area-level poverty,[52] subgroup analyses were conducted within strata defined by these factors. In subgroup analysis, age was dichotomized based on members' median age upon cohort entry (younger than 75 years vs 75 years or older). For all subgroup analyses, Cochran *Q* statistics were calculated to assess for heterogeneity.[53]

Sensitivity Analyses

Natural splines were used to capture potential nonlinear associations. We additionally calculated the controlled direct effect after eliminating loss to follow-up and the competing risk of death using the product of inverse probability of censoring weights and inverse probability of death weights.[54]

Results

Of 1 640 220 eligible KPSC members aged 60 years or older between January 1, 2008, and January 1, 2019, 245 389 members (15.0%) were excluded because they did not satisfy criteria for continuous enrollment, and 134 111 members (8.2%) were excluded who were not 60 years old in the qualifying year. We excluded 10 274 members (0.6%) missing census tract of residence, 27 003 (1.6%) with a dementia diagnosis before cohort entry, and 339 (less than 0.1%) with missing sex data or rural-urban commuting area codes. This yielded a final study population of 1 223 107 members (eFigure 1 in Supplement 1). Over the study period, 80 884 beneficiaries (6.6%) received a dementia diagnosis, 119 435 (9.8%) died, and 156 310 (13.0%) were lost to follow-up. Most members diagnosed with dementia (69.0%) were diagnosed with nonspecific dementia (eTable 2 in Supplement 1). Approximately half of the study population were female (53.0%), identified as non-Hispanic White (49.0%), and were married or partnered (54.0%; **Table**). Members diagnosed with dementia during the study period

Table. Characteristics of the Kaiser Permanente Southern California (KPSC) Study Population, 2008-2019

Characteristic	Study population, No. (%)		
		During follow-up	
	Overall (N = 1 223 107)	Dementia-free (n = 1 142 223)	Incident dementia (n = 80 884)[a]
Sex			
Female	649 766 (53.0)	603 827 (53.0)	45 939 (57.0)
Male	573 341 (47.0)	538 396 (47.0)	34 945 (43.0)
Age at cohort entry, median (IQR), y	62 (60-69)	62 (60-68)	76 (70-82)
Race and ethnicity			
Hispanic	319 521 (26.0)	302 737 (27.0)	16 784 (21.0)
Non-Hispanic			
Asian	128 611 (11.0)	122 860 (11.0)	5751 (7.1)
Black	114 889 (9.4)	104 805 (9.2)	10 084 (12.0)
White	601 334 (49.0)	554 337 (49.0)	46 997 (58.0)
Other[b]	58 752 (4.8)	57 484 (5.0)	1268 (1.6)
Relationship status			
Married or partnered	662 195 (54.0)	626 862 (55.0)	35 333 (44.0)
Divorced or separated	118 585 (9.7)	110 075 (9.6)	8510 (11.0)
Single	147 649 (12.0)	142 147 (12.0)	5502 (6.8)
Widowed	163 971 (13.0)	135 213 (12.0)	28 758 (36.0)
Other or unknown	130 707 (11.0)	127 926 (11.0)	2781 (3.4)
Smoking status			
Never, passive, or unknown	752 112 (61.0)	708 825 (62.0)	43 287 (54.0)
Former smoker	408 697 (33.0)	373 496 (33.0)	35 201 (44.0)
Current smoker	62 298 (5.1)	59 902 (5.2)	2396 (3.0)
Deaths during follow-up	119 435 (9.8)	114 104 (10.0)	5331 (6.6)
Lost to follow-up	156 310 (13.0)	155 954 (14.0)	356 (0.4)
Required interpreter	133 411 (11.0)	127 465 (11.0)	5946 (7.4)
Census tract–level characteristics, median (IQR)[c]			
Poverty, %	9 (5-16)	9 (5-16)	9 (5-16)
Population density, individuals per km^2	2494 (1267-3898)	2487 (1257-3904)	2530 (1372-3869)

[a] Dementia diagnoses made in the inpatient and outpatient setting between January 1, 2008, and December 31, 2019, were ascertained through the electronic health record. Diagnostic codes from the *International Classification of Diseases, Ninth* and *Tenth Revisions* were used to identify incident diagnoses of Alzheimer disease, Lewy body dementia, vascular dementia, and other dementias (eTable 1 in Supplement 1).

[b] "Other" category includes individuals of multiple races, individuals of unknown race and ethnicity, individuals of other ethnicity, and Native American and Alaskan Native and Pacific Islander individuals.

[c] Census tract–level covariates were obtained from the 2010 US Census based on geocoded member address.

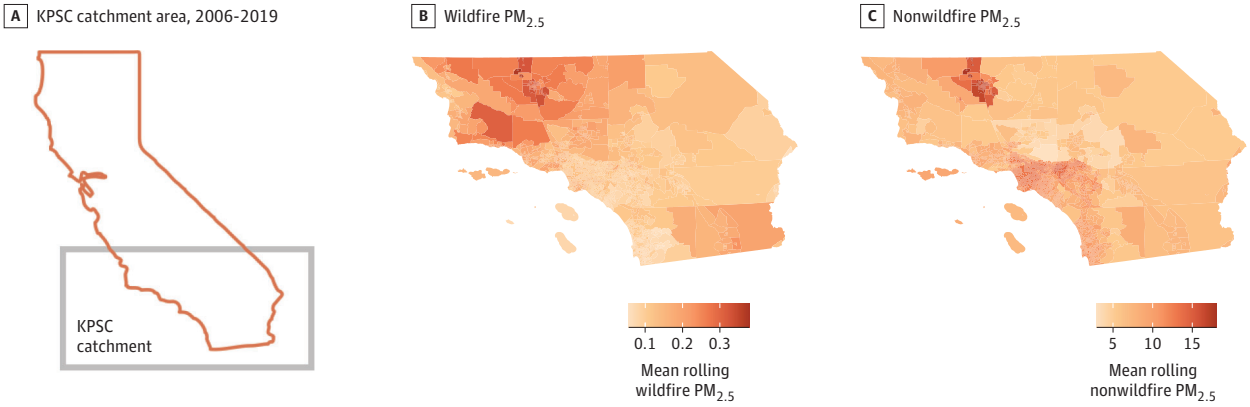
were more often non-Hispanic White, widowed, or former smokers or nonsmokers and were less likely to require the use of an interpreter for health care encounters. Those with and without dementia lived in census tracts with similar population density and poverty percentages. Over the study period, the median (IQR) 3-year rolling average for wildfire $PM_{2.5}$ concentration was 0.09 μg/m^3 (0.05-0.16), and the median (IQR) nonwildfire $PM_{2.5}$ concentration was 11.2 μg/m^3 (9.6-12.4) (**Figure 1**; eTable 3 in Supplement 1).

In adjusted models, an 18% increase in the odds of dementia diagnosis was observed for every 1-μg/m^3 increase in 3-year average wildfire $PM_{2.5}$ concentration (odds ratio [OR], 1.18; 95% CI, 1.03-1.34) (**Figure 2**). For nonwildfire $PM_{2.5}$, the odds of dementia diagnosis increased by 1% for every 1-μg/m^3 increase in 3-year mean exposure (OR, 1.01; 95% CI, 1.01-1.02) (Figure 2). This indicates that for the same concentration change, dementia risk associated with wildfire $PM_{2.5}$ was higher than dementia risk associated with $PM_{2.5}$ from other sources. Estimating the association for an IQR increase in wildfire $PM_{2.5}$ (0.11 μg/m^3) and nonwildfire $PM_{2.5}$ (2.8 μg/m^3), similar odds ratios were found (OR, 1.02; 95% CI, 1.00-1.03; and OR, 1.03; 95% CI, 1.02-1.04, respectively) (eTable 4 in Supplement 1).

We assessed alternative wildfire $PM_{2.5}$ exposure metrics and observed an association between a 10-μg/m^3 increase in wildfire $PM_{2.5}$ concentration during the peak exposure week (OR, 1.02; 95% CI, 1.00-1.05) and 1 additional smoke wave (OR, 1.03; 95% CI, 1.01-1.05) with dementia diagnosis (eTable 4 in Supplement 1). The association was weaker for an additional week where wildfire $PM_{2.5}$ was greater than 5 μg/m^3 (OR, 1.01; 95% CI, 0.99-1.02) or 38 additional days where wildfire $PM_{2.5}$ was greater than 0 μg/m^3 (OR, 1.01; 95% CI, 0.99-1.03).

Secondary analyses suggested stronger relative associations among younger members upon study entry (age less than 75 years vs age 75 years or more), men vs women, and those living in high-poverty vs low-poverty census tracts. However, evidence of heterogeneity was only identified for age category (*P* value for heterogeneity, <.001; Figure 2). Although imprecise, subgroup results suggested stronger associations among racially minoritized subgroups (Hispanic: OR, 1.09; 95% CI, 0.79-1.48; non-Hispanic Asian: OR, 1.62; 95% CI, 0.86-2.98; non-Hispanic Black: OR, 1.47; 95% CI, 0.92-2.34; non-Hispanic White: OR, 1.02; 95% CI, 0.87-1.20; *P* value for heterogeneity, .01; Figure 2). The "Other" group, containing individuals of multiple races, individuals of unknown race and

Figure 1. Mean Census Tract–Level Wildfire and Nonwildfire Fine Particulate Matter ($PM_{2.5}$) Smoke Exposure, 2006-2019



Using daily estimates across the Kaiser Permanente Southern California (KPSC) catchment area (A), census tract–level wildfire $PM_{2.5}$ concentrations (B) and nonwildfire $PM_{2.5}$ concentrations (C) were calculated as time-varying 3-year rolling means, updated quarterly. Wildfire and nonwildfire $PM_{2.5}$ exposure estimates were assigned to study participants based on their time-varying residential address geocoded to the census tract level. Shaded areas represent the mean of all quarter-specific 3-year rolling mean $PM_{2.5}$ concentrations (in $\mu g/m^3$) in the KPSC catchment area, 2006-2019.

ethnicity, individuals of other race, and Native American and Alaskan Native and Pacific Islander individuals had the highest odds of dementia per unit increase in wildfire $PM_{2.5}$ exposure (OR, 3.45; 95% CI, 1.66-6.93). For nonwildfire $PM_{2.5}$, a stronger association was observed among men than among women (*P* value for heterogeneity, .01) but no clear differences were observed by race and ethnicity or census tract poverty (Figure 2).

In sensitivity analyses, a nearly-linear exposure-response association was found for wildfire $PM_{2.5}$ (eFigure 2 in Supplement 1), whereas the association between nonwildfire $PM_{2.5}$ concentration and dementia diagnosis increased up to approximately 6.5 $\mu g/m^3$, flattened through approximately 13 $\mu g/m^3$, and then increased (eFigure 3 in Supplement 1). Results were robust when competing risk of death and loss to follow-up were eliminated (eTable 5 in Supplement 1).

Discussion

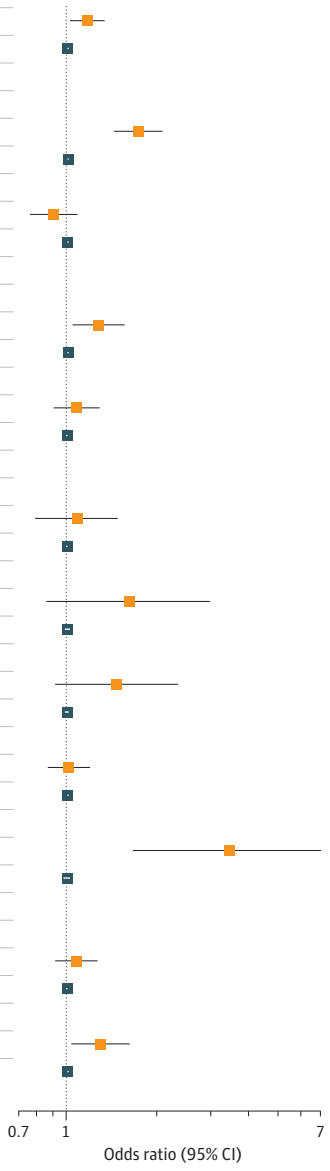
This January 2008 to December 2019 Southern California cohort study identified wildfire $PM_{2.5}$ as a potentially important risk factor for dementia. Among more than 1.2 million eligible KPSC members, each 1-$\mu g/m^3$ increase in long-term wildfire $PM_{2.5}$ exposure was associated with an 18% increase in the odds of dementia diagnosis. Secondary analyses suggested that members aged less than 75 years, those from racially minoritized groups, and those living in high-poverty census tracts had heightened responses to wildfire $PM_{2.5}$ exposure. These results align with prior research consistently demonstrating that individual-level and area-level social determinants compound the risk of adverse health outcomes associated with climate-driven environmental exposures.[55,56]

Past research has consistently identified an association between long-term $PM_{2.5}$ exposure and incident dementia,[38,57] with varying magnitudes of association depending on study context, outcome ascertainment, and exposure averaging period.[11,38,58-60] For example, among Medicare beneficiaries aged 65 years or older, Shi and colleagues[61] found that each interquartile increase in the 5-year mean $PM_{2.5}$ concentration was associated with a 6% greater risk of dementia diagnosis. Using neurologist-adjudicated dementia cases based on neuropsychological testing and magnetic resonance imaging, Semmens and colleagues[62] found that among 3069 adults aged 75 years or older recruited across 4 US study sites in the Gingko Evaluation of Memory Study, a 2-$\mu g/m^3$ increase in 20-year mean $PM_{2.5}$ exposure was associated with a 20% higher risk of dementia. Two recent meta-analyses[38,57] reported 4% greater dementia risk for each 2-$\mu g/m^3$ increase and a 3% greater dementia risk for each 3-$\mu g/m^3$ increase in $PM_{2.5}$, respectively. In line with these results, we estimated a 1% increase in risk for incident dementia with each 1-$\mu g/m^3$ increase in the 3-year mean nonwildfire $PM_{2.5}$ concentration.

This study offers a critical extension of prior work, demonstrating increased odds of dementia associated with long-term wildfire and nonwildfire $PM_{2.5}$ among 1.2 million older Southern California residents. These results further suggest a stronger association between wildfire $PM_{2.5}$ exposure and subsequent dementia, in keeping with a strong theoretical basis suggesting unique toxic neurologic effects of wildfire $PM_{2.5}$. Wildfire $PM_{2.5}$ contains higher concentrations of oxidative and pro-inflammatory compounds,[63-66] has a smaller average particle size,[32] and is generated by combustion of organic materials at substantially higher temperatures than nonwildfire $PM_{2.5}$.[33] Further, wildfire $PM_{2.5}$ concentrations tend to spike intermittently at high levels, contrasting with more consistent exposure to nonwildfire $PM_{2.5}$ throughout the year.[48] Using alternative measures of long-term wildfire $PM_{2.5}$ exposure, we found increased odds of dementia diagnosis associated with mean peak week exposure and smoke waves, but not weeks where wildfire $PM_{2.5}$ was greater than 5 $\mu g/m^3$ or days where wildfire $PM_{2.5}$ was greater than 0 $\mu g/m^3$. Because peak week exposure and smoke waves explicitly capture short-term increases in

Figure 2. Association of 3-Year Mean Wildfire and Nonwildfire Fine Particulate Matter ($PM_{2.5}$) Exposure With Dementia Diagnosis[1] Among Kaiser Permanente Southern California (KPSC) Members Aged 60 Years or Older, 2008-2019

Category	Odds ratio (95% CI)
Overall	
Wildfire $PM_{2.5}$	1.18 (1.03-1.34)
Nonwildfire $PM_{2.5}$	1.01 (1.01-1.02)
Age, y	
<75	
Wildfire $PM_{2.5}$	1.73 (1.44-2.08)
Nonwildfire $PM_{2.5}$	1.02 (1.01-1.02)
≥75	
Wildfire $PM_{2.5}$	0.91 (0.76-1.09)
Nonwildfire $PM_{2.5}$	1.01 (1.01-1.02)
Sex	
Male	
Wildfire $PM_{2.5}$	1.28 (1.05-1.56)
Nonwildfire $PM_{2.5}$	1.02 (1.01-1.02)
Female	
Wildfire $PM_{2.5}$	1.08 (0.91-1.29)
Nonwildfire $PM_{2.5}$	1.01 (1.00-1.01)
Race and ethnicity	
Hispanic	
Wildfire $PM_{2.5}$	1.09 (0.79-1.48)
Nonwildfire $PM_{2.5}$	1.01 (1.00-1.01)
Non-Hispanic Asian	
Wildfire $PM_{2.5}$	1.62 (0.86-2.98)
Nonwildfire $PM_{2.5}$	1.01 (0.99-1.03)
Non-Hispanic Black	
Wildfire $PM_{2.5}$	1.47 (0.92-2.34)
Nonwildfire $PM_{2.5}$	1.01 (0.99-1.02)
Non-Hispanic White	
Wildfire $PM_{2.5}$	1.02 (0.87-1.20)
Nonwildfire $PM_{2.5}$	1.01 (1.01-1.02)
Other	
Wildfire $PM_{2.5}$	3.45 (1.66-6.93)
Nonwildfire $PM_{2.5}$	1.01 (0.98-1.03)
Area-level poverty	
Low	
Wildfire $PM_{2.5}$	1.08 (0.92-1.27)
Nonwildfire $PM_{2.5}$	1.01 (1.00-1.01)
High	
Wildfire $PM_{2.5}$	1.30 (1.04-1.62)
Nonwildfire $PM_{2.5}$	1.01 (1.01-1.02)



A discrete-time approach with pooled logistic regression was used to estimate the odds of dementia diagnoses. Models controlled for age at study entry (natural cubic spline), sex, race and ethnicity, smoking status, relationship status, whether the participant required an interpreter during health care encounters, calendar year, and census tract–level population density and poverty. Estimates are depicted overall and by subgroup. Model coefficients correspond to a 1-μg/m^3 increase in wildfire and nonwildfire $PM_{2.5}$ concentrations. Overall effect estimates are provided and stratified by potential effect measure modifiers: median age at cohort entry (wildfire $PM_{2.5}$ *P* value for heterogeneity, <.001; nonwildfire $PM_{2.5}$ *P* value for heterogeneity, .49), sex (wildfire $PM_{2.5}$ *P* value for heterogeneity, .39; nonwildfire $PM_{2.5}$ *P* value for heterogeneity, .01), race and ethnicity (wildfire $PM_{2.5}$ *P* value for heterogeneity, .01; nonwildfire $PM_{2.5}$ *P* value for heterogeneity, .92), and census tract–level poverty (wildfire $PM_{2.5}$ *P* value for heterogeneity, .17; nonwildfire $PM_{2.5}$ *P* value for heterogeneity, .35). OR indicates odds ratio.

wildfire $PM_{2.5}$ concentration, these results suggest that these high levels may pose particular risk.

The results of this study are consistent with prior studies that have suggested dementia risk varies based on $PM_{2.5}$ components. Zhang and colleagues[31] found agriculture, traffic, coal combustion, and wildfire-generated $PM_{2.5}$ were the individual components most strongly associated with dementia among 27 857 members older than 50 years in the Health and Retirement Study from 1998 to 2016. They observed a 5% increase in the risk of dementia for a 0.6-μg/m^3 increase in wildfire-specific $PM_{2.5}$, measured only in 2017 but extrapolated across 10 years. Using data on more than 18.5 million Medicare beneficiaries from 2000 to 2017, Shi and colleagues[67] examined the association of long-term exposure to $PM_{2.5}$ subcomponents with all-cause dementia. Although this study observed associations with $PM_{2.5}$ subcomponents that also comprise wildfire $PM_{2.5}$ (including black carbon, organic matter, and sulfate), their analysis did not explicitly consider the association between wildfire $PM_{2.5}$ and incident dementia. This analysis builds on these 2 prior studies, leveraging novel long-term measures of $PM_{2.5}$ produced by wildfire events.

In subanalyses, it was found that wildfire $PM_{2.5}$ exposure was only associated with dementia diagnosis among those aged less than 75 years upon cohort entry. Possible factors contributing to this finding may include differences in time spent outdoors with higher actual wildfire $PM_{2.5}$ exposure among those

aged less than 75 years; that members most susceptible to wildfire $PM_{2.5}$ exposure may have died sooner and thus were not present in the subgroup of members aged 75 years or older upon cohort entry; or lower baseline risk of dementia among younger members, which could contribute to higher effect estimates on the relative scale.

Finally, these results suggest the association between long-term wildfire $PM_{2.5}$ exposure and dementia differed substantially based on individual race and ethnicity and area poverty. In the US, environmental exposures disproportionately impact racially and economically marginalized groups,[68,69] and these groups may further experience differential health effects of wildfire $PM_{2.5}$ exposure. For example, lower-quality housing may increase smoke infiltration, and poorer families may have constrained economic choices[70] that limit their ability to pay for air filtration systems to improve air quality during smoke events.[71] Future studies may wish to explicitly study these factors as effect modifiers. Members of marginalized groups may have amplified physiologic responses to environmental exposures, reflecting worse baseline health, the cumulative result of discrimination, and chronic exposure to psychosocial stressors.[56,72-75] Consistent with this theoretical framework, the strongest associations were observed among non-Hispanic Asian, non-Hispanic Black, and Hispanic members and those living in areas characterized by high poverty. Continued focus on differential health risks from wildfire $PM_{2.5}$ exposure within subpopulations—and the mechanisms that underlie these differences—may advance health equity in a changing climate and should remain an essential focus for future scholarship.

Limitations

We estimated long-term wildfire and nonwildfire $PM_{2.5}$ exposure over a 3-year period. The causally relevant window of exposure for $PM_{2.5}$ and dementia remains unknown.[38] Because the neurodegenerative processes underlying dementia likely begin years before clinical symptoms emerge, future research should consider longer exposure durations. Further, the most biologically relevant measure for estimating exposure to long-term wildfire $PM_{2.5}$ has not yet been determined.[48] Notably, we estimated the association for each 1-$\mu g/m^3$ increase in long-term wildfire $PM_{2.5}$ concentrations, a value larger than the IQR for the observed distribution of wildfire $PM_{2.5}$. However, in sensitivity analyses, we have also presented results using an IQR increase in both wildfire and nonwildfire $PM_{2.5}$, which are consistent with findings from our main analysis. Although wildfire smoke leads to increased concentrations of ozone and other gaseous pollutants like volatile organic compounds,[76,77] these have inconclusive associations with incident dementia.[38] We focused on wildfire $PM_{2.5}$, the most health-relevant component of wildfire smoke. Future work exploring specific effects of other wildfire smoke pollutants may help further characterize its health impacts.

ICD-9 and *ICD-10* diagnostic codes were used to ascertain cases of incident dementia. A 2023 meta-analysis[38] found stronger associations between $PM_{2.5}$ and dementia in studies that used active vs passive (diagnostic code) case ascertainment. We anticipate that outcome misclassification resulting from the use of diagnostic codes did not occur systematically with respect to long-term wildfire and nonwildfire $PM_{2.5}$ exposure and therefore likely biased estimates toward the null. Reliance on diagnostic codes further precludes evaluation of dementia subtypes, which might otherwise yield novel insights into the mechanisms underlying observed associations.

Although our analysis leveraged data from more than 1.2 million KPSC beneficiaries, we lacked sufficient power to examine associations within some critical demographic subgroups (eg, Native American beneficiaries who may have elevated wildfire $PM_{2.5}$ exposure).[48] EHR data did not contain measures of behavior change in response to wildfire $PM_{2.5}$ exposure, such as masking or limiting time spent outdoors, which could plausibly mitigate dementia risk. We could not fully account for socioeconomic factors that might correlate with the ability to afford air filtration systems, receive public health messaging, or shelter indoors.[70] We aimed to minimize confounding by adjusting for sociodemographic factors in all statistical models, but the possibility of residual confounding cannot be eliminated in this observational study.

Conclusions

Among more than 1.2 million KPSC members, long-term wildfire smoke exposure was associated with subsequent dementia diagnosis. This risk was more pronounced among racially minoritized patient subgroups and among those living in high-poverty census tracts. These latter findings underscore the importance of research that considers the effects of air pollution on potentially vulnerable population subgroups and aims to identify potential strategies to mitigate inequities in air pollution exposure effects.

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REFERENCES

1. Burke M, Driscoll A, Heft-Neal S, Xue J, Burney J, Wara M. The changing risk and burden of wildfire in the United States. *Proc Natl Acad Sci USA*. 2021;118(2):e2011048118. doi:10.1073/pnas.2011048118

2. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. *Proc Natl Acad Sci USA*. 2016;113(42):11770-11775. doi:10.1073/pnas.1607171113

3. Halofsky JE, Peterson DL, Harvey BJ. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*. 2020;16(1):1-26. doi:10.1186/s42408-019-0062-8

4. Williams AP, Abatzoglou JT, Gershunov A, et al. Observed impacts of anthropogenic climate change on wildfire in California. *Earths Future*. 2019;7(8):892-910. doi:10.1029/2019EF001210

5. Burke M, Childs ML, de la Cuesta B, et al. The contribution of wildfire to $PM_{2.5}$ trends in the USA. *Nature*. 2023;622(7984):761-766. doi:10.1038/s41586-023-06522-6

6. Liu JC, Mickley LJ, Sulprizio MP, et al. Particulate air pollution from wildfires in the Western US under climate change. *Climate Change*. 2016;138(3):655-666. doi:10.1007/s10584-016-1762-6

7. Wang D, Guan D, Zhu S, et al. Economic footprint of California wildfires in 2018. *Nat Sustainability*. 2021;4(3):252-260. doi:10.1038/s41893-020-00646-7

8. Reid J, Koppmann R, Eck T, Eleuterio D. A review of biomass burning emissions part II: intensive physical properties of biomass burning particles. *Atmospheric Chem Phys*. 2005;5(3):799-825. doi:10.5194/acp-5-799-2005

9. Liu JC, Wilson A, Mickley LJ, et al. Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. *Epidemiology*. 2017;28(1):77-85. doi:10.1097/EDE.0000000000000556

10. Xing YF, Xu YH, Shi MH, Lian YX. The impact of PM2.5 on the human respiratory system. *J Thorac Dis*. 2016;8(1):E69-E74.

11. Weuve J, Bennett EE, Ranker L, et al. Exposure to air pollution in relation to risk of dementia and related outcomes: an updated systematic review of the epidemiological literature. *Environ Health Perspect*. 2021;129(9):96001. doi:10.1289/EHP8716

12. Block ML, Calderón-Garcidueñas L. Air pollution: mechanisms of neuroinflammation and CNS disease. *Trends Neurosci*. 2009;32(9):506-516. doi:10.1016/j.tins.2009.05.009

13. Heusinkveld HJ, Wahle T, Campbell A, et al. Neurodegenerative and neurological disorders by small inhaled particles. *Neurotoxicology*. 2016;56:94-106. doi:10.1016/j.neuro.2016.07.007

14. Jayaraj RL, Rodriguez EA, Wang Y, Block ML. Outdoor ambient air pollution and neurodegenerative diseases: the neuroinflammation hypothesis. *Curr Environ Health Rep*. 2017;4(2):166-179. doi:10.1007/s40572-017-0142-3

15. Calderón-Garcidueñas L, Mora-Tiscareño A, Ontiveros E, et al. Air pollution, cognitive deficits and brain abnormalities: a pilot study with children and dogs. *Brain Cogn*. 2008;68(2):117-127. doi:10.1016/j.bandc.2008.04.008

16. Levesque S, Taetzsch T, Lull ME, et al. Diesel exhaust activates and primes microglia: air pollution, neuroinflammation, and regulation of dopaminergic neurotoxicity. *Environ Health Perspect*. 2011;119(8):1149-1155. doi:10.1289/ehp.1002986

17. Calderón-Garcidueñas L, Solt AC, Henríquez-Roldán C, et al. Long-term air pollution exposure is associated with neuroinflammation, an altered innate immune response, disruption of the blood-brain barrier, ultrafine particulate deposition, and accumulation of amyloid β-42 and α-synuclein in children and young adults. *Toxicol Pathol*. 2008;36(2):289-310. doi:10.1177/0192623307313011

18. Jensen O, Parkin D, MacLennan R, Muir C, Skeet R, eds. *Cancer Registration: Principles and Methods*. International Agency for Research on Cancer, International Association of Cancer Registries; 1991.

19. Oppenheim HA, Lucero J, Guyot AC, et al. Exposure to vehicle emissions results in altered blood brain barrier permeability and expression of matrix metalloproteinases and tight junction proteins in mice. *Particle Fibre Toxicol*. 2013;10(1):62. doi:10.1186/1743-8977-10-62

20. Block ML, Zecca L, Hong JS. Microglia-mediated neurotoxicity: uncovering the molecular mechanisms. *Nat Rev Neurosci*. 2007;8(1):57-69. doi:10.1038/nrn2038

21. Block ML, Elder A, Auten RL, et al. The outdoor air pollution and brain health workshop. *Neurotoxicology*. 2012;33(5):972-984. doi:10.1016/j.neuro.2012.08.014

22. Oberdörster G, Sharp Z, Atudorei V, et al. Translocation of inhaled ultrafine particles to the brain. *Inhalational Toxicol*. 2004;16(6-7):437-445. doi:10.1080/08958370490439597

23. Mühlfeld C, Rothen-Rutishauser B, Blank F, Vanhecke D, Ochs M, Gehr P. Interactions of nanoparticles with pulmonary structures and cellular responses. *Am J Physiol Lung Cell Mol Physiol*. 2008;294(5):L817-L829. doi:10.1152/ajplung.00442.2007

24. Lucchini RG, Dorman DC, Elder A, Veronesi B. Neurological impacts from inhalation of pollutants and the nose-brain connection. *Neurotoxicology*. 2012;33(4):838-841. doi:10.1016/j.neuro.2011.12.001

25. Ljungman PL, Mittleman MA. Ambient air pollution and stroke. *Stroke*. 2014;45(12):3734-3741. doi:10.1161/STROKEAHA.114.003130

26. von Bornstädt D, Kunz A, Endres M. Impact of particulate matter exposition on the risk of ischemic stroke: epidemiologic evidence and putative mechanisms. *J Cereb Blood Flow Metab*. 2014;34(2):215-220. doi:10.1038/jcbfm.2013.212

27. Baumgart M, Snyder HM, Carrillo MC, Fazio S, Kim H, Johns H. Summary of the evidence on modifiable risk factors for cognitive decline and dementia: a population-based perspective. *Alzheimers Dement*. 2015;11(6):718-726. doi:10.1016/j.jalz.2015.05.016

28. Shah AS, Lee KK, McAllister DA, et al. Short term exposure to air pollution and stroke: systematic review and meta-analysis. *BMJ*. 2015;350:h1295. doi:10.1136/bmj.h1295

29. Shin HH, Fann N, Burnett RT, Cohen A, Hubbell BJ. Outdoor fine particles and nonfatal strokes: systematic review and meta-analysis. *Epidemiology*. 2014;25(6):835-842. doi:10.1097/EDE.0000000000000162

30. Wellenius GA, Boyle LD, Wilker EH, et al. Ambient fine particulate matter alters cerebral hemodynamics in the elderly. *Stroke*. 2013;44(6):1532-1536. doi:10.1161/STROKEAHA.111.000395

31. Zhang B, Weuve J, Langa KM, et al. Comparison of particulate air pollution from different emission sources and incident dementia in the US. *JAMA Intern Med*. 2023;183(10):1080-1089. doi:10.1001/jamainternmed.2023.3300

32. Makkonen U, Hellén H, Anttila P, Ferm M. Size distribution and chemical composition of airborne particles in south-eastern Finland during different seasons and wildfire episodes in 2006. *Sci Total Environ*. 2010;408(3):644-651. doi:10.1016/j.scitotenv.2009.10.050

33. Vardoulakis S, Jalaludin BB, Morgan GG, Hanigan IC, Johnston FH. Bushfire smoke: urgent need for a national health protection strategy. *Med J Aust*. 2020;212(8):349-353.e1. doi:10.5694/mja2.50511

34. Kaiser Permanente Southern California Department of Research and Evaluation. Fast facts: southern California research program. Accessed

February 1, 2024. https://www.kp-scalresearch.org/aboutus/fast-facts/

35. Koebnick C, Langer-Gould AM, Gould MK, et al. Sociodemographic characteristics of members of a large, integrated health care system: comparison with US Census Bureau data. *Permanente J*. 2012;16(3):37-41. doi:10.7812/TPP/12-031

36. Aguilera R, Luo N, Basu R, et al. A novel ensemble-based statistical approach to estimate daily wildfire-specific $PM_{2.5}$ in California (2006-2020). *Environ Int*. 2023;171:107719. doi:10.1016/j.envint.2022.107719

37. Abatzoglou JT. Development of gridded surface meteorological data for ecological applications and modelling. *Int J Climatology*. 2013;33(1):121-131. doi:10.1002/joc.3413

38. Wilker EH, Osman M, Weisskopf MG. Ambient air pollution and clinical dementia: systematic review and meta-analysis. *BMJ*. 2023;381:e071620. doi:10.1136/bmj-2022-071620

39. Gilsanz P, Mayeda ER, Glymour MM, Quesenberry CP, Whitmer RA. Association between birth in a high stroke mortality state, race, and risk of dementia. *JAMA Neurol*. 2017;74(9):1056-1062. doi:10.1001/jamaneurol.2017.1553

40. Mayeda ER, Glymour MM, Quesenberry CP, Whitmer RA. Inequalities in dementia incidence between six racial and ethnic groups over 14 years. *Alzheimers Dement*. 2016;12(3):216-224. doi:10.1016/j.jalz.2015.12.007

41. Whitmer RA, Sidney S, Selby J, Johnston SC, Yaffe K. Midlife cardiovascular risk factors and risk of dementia in late life. *Neurology*. 2005;64(2):277-281. doi:10.1212/01.WNL.0000149519.47454.F2

42. Whitmer RA, Gustafson DR, Barrett-Connor E, Haan MN, Gunderson EP, Yaffe K. Central obesity and increased risk of dementia more than three decades later. *Neurology*. 2008;71(14):1057-1064. doi:10.1212/01.wnl.0000306313.89165.ef

43. Katon WJ, Lin EH, Williams LH, et al. Comorbid depression is associated with an increased risk of dementia diagnosis in patients with diabetes: a prospective cohort study. *J Gen Intern Med*. 2010;25(5):423-429. doi:10.1007/s11606-009-1248-6

44. Manson S, Schroeder J, Riper DV, Ruggles S. National Historical Geographic Information System: version 12.0 [dataset]. University of Minnesota. Accessed February 1, 2024. doi:10.18128/D050.V12.0

45. de Bont J, Jaganathan S, Dahlquist M, Persson Å, Stafoggia M, Ljungman P. Ambient air pollution and cardiovascular diseases: an umbrella review of systematic reviews and meta-analyses. *J Intern Med*. 2022;291(6):779-800. doi:10.1111/joim.13467

46. McGuinn LA, Schneider A, McGarrah RW, et al. Association of long-term $PM_{2.5}$ exposure with traditional and novel lipid measures related to cardiovascular disease risk. *Environ Int*. 2019;122:193-200. doi:10.1016/j.envint.2018.11.001

47. Zhao M, Xu Z, Guo Q, Gan Y, Wang Q, Liu JA. Association between long-term exposure to $PM_{2.5}$ and hypertension: a systematic review and meta-analysis of observational studies. *Environ Res*. 2022;204(pt D):112352. doi:10.1016/j.envres.2021.112352

48. Casey JA, Kioumourtzoglou MA, Padula A, et al. Measuring long-term exposure to wildfire $PM_{2.5}$ in California: time-varying inequities in environmental burden. *Proc Natl Acad Sci USA*. 2024;121(8):e2306729121. doi:10.1073/pnas.2306729121

49. Hebert LE, Weuve J, Scherr PA, Evans DA. Alzheimer disease in the United States (2010-2050) estimated using the 2010 census. *Neurology*. 2013;80(19):1778-1783. doi:10.1212/WNL.0b013e31828726f5

50. Mazure CM, Swendsen J. Sex differences in Alzheimer's disease and other dementias. *Lancet Neurol*. 2016;15(5):451-452. doi:10.1016/S1474-4422(16)00067-3

51. Mehta KM, Yeo GW. Systematic review of dementia prevalence and incidence in United States race/ethnic populations. *Alzheimers Dement*. 2017;13(1):72-83. doi:10.1016/j.jalz.2016.06.2360

52. Dintica CS, Bahorik A, Xia F, Kind A, Yaffe K. Dementia risk and disadvantaged neighborhoods. *JAMA Neurol*. 2023;80(9):903-909. doi:10.1001/jamaneurol.2023.2120

53. Kaufman JS, MacLehose RF. Which of these things is not like the others? *Cancer*. 2013;119(24):4216-4222. doi:10.1002/cncr.28359

54. Young JG, Stensrud MJ, Tchetgen Tchetgen EJ, Hernán MA. A causal framework for classical statistical estimands in failure-time settings with competing events. *Stat Med*. 2020;39(8):1199-1236. doi:10.1002/sim.8471

55. Morello-Frosch R, Obasogie OK. The climate gap and the color line—racial health inequities and climate change. *N Engl J Med*. 2023;388(10):943-949. doi:10.1056/NEJMsb2213250

56. Smith GS, Anjum E, Francis C, Deanes L, Acey C. Climate change, environmental disasters, and health inequities: the underlying role of structural inequalities. *Curr Environ Health Rep*. 2022;9(1):80-89. doi:10.1007/s40572-022-00336-w

57. Abolhasani E, Hachinski V, Ghazaleh N, Azarpazhooh MR, Mokhber N, Martin J. Air pollution and incidence of dementia: a systematic review and meta-analysis. *Neurology*. 2023;100(2):e242-e254. doi:10.1212/WNL.0000000000201419

58. Tsai TL, Lin YT, Hwang BF, et al. Fine particulate matter is a potential determinant of Alzheimer's disease: a systemic review and meta-analysis. *Environ Res*. 2019;177:108638. doi:10.1016/j.envres.2019.108638

59. Shaffer RM, Blanco MN, Li G, et al. Fine particulate matter and dementia incidence in the adult changes in thought study. *Environ Health Perspect*. 2021;129(8):87001. doi:10.1289/EHP9018

60. Sullivan KJ, Ran X, Wu F, et al. Ambient fine particulate matter exposure and incident mild cognitive impairment and dementia. *J Am Geriatr Soc*. 2021;69(8):2185-2194. doi:10.1111/jgs.17188

61. Shi L, Steenland K, Li H, et al. A national cohort study (2000-2018) of long-term air pollution exposure and incident dementia in older adults in the United States. *Nat Commun*. 2021;12(1):6754. doi:10.1038/s41467-021-27049-2

62. Semmens EO, Leary CS, Fitzpatrick AL, et al. Air pollution and dementia in older adults in the Ginkgo Evaluation of Memory Study. *Alzheimers Dement*. 2023;19(2):549-559. doi:10.1002/alz.12654

63. Verma V, Polidori A, Schauer JJ, Shafer MM, Cassee FR, Sioutas C. Physicochemical and toxicological profiles of particulate matter in Los Angeles during the October 2007 southern California wildfires. *Environ Sci Technol*. 2009;43(3):954-960. doi:10.1021/es8021667

64. Balmes JR. The changing nature of wildfires: impacts on the health of the public. *Clin Chest Med*. 2020;41(4):771-776. doi:10.1016/j.ccm.2020.08.006

65. Masselot P, Sera F, Schneider R, et al. Differential mortality risks associated with PM2.5 components: a multi-country, multi-city study. *Epidemiology*. 2022;33(2):167-175. doi:10.1097/EDE.0000000000001455

66. Wegesser TC, Pinkerton KE, Last JA. California wildfires of 2008: coarse and fine particulate matter toxicity. *Environ Health Perspect*. 2009;117(6):893-897. doi:10.1289/ehp.0800166

67. Shi L, Zhu Q, Wang Y, et al. Incident dementia and long-term exposure to constituents of fine particle air pollution: a national cohort study in the United States. *Proc Natl Acad Sci USA*. 2023;120(1):e2211282119. doi:10.1073/pnas.2211282119

68. Pulido L. A critical review of the methodology of environmental racism research. *Antipode*. 1996;28(2):142-159. doi:10.1111/j.1467-8330.1996.tb00519.x

69. Szasz A, Meuser M. Environmental inequalities: literature review and proposals for new directions in research and theory. *Curr Sociol*. 1997;45(3):99-120. doi:10.1177/001139297045003006

70. Burke M, Heft-Neal S, Li J, et al. Exposures and behavioural responses to wildfire smoke. *Nat Hum Behav*. 2022;6(10):1351-1361. doi:10.1038/s41562-022-01396-6

71. Krebs B, Neidell M. Wildfires exacerbate inequalities in indoor pollution exposure. *Environ Res Lett*. 2024;19(2):024043. doi:10.1088/1748-9326/ad22b8

72. Laurent O, Bard D, Filleul L, Segala C. Effect of socioeconomic status on the relationship between atmospheric pollution and mortality. *J Epidemiol Community Health*. 2007;61(8):665-675. doi:10.1136/jech.2006.053611

73. Morello-Frosch R, Shenassa ED. The environmental "riskscape" and social inequality: implications for explaining maternal and child health disparities. *Environ Health Perspect*. 2006;114(8):1150-1153. doi:10.1289/ehp.8930

74. Hajat A, Hsia C, O'Neill MS. Socioeconomic disparities and air pollution exposure: a global review. *Curr Environ Health Rep*. 2015;2(4):440-450. doi:10.1007/s40572-015-0069-5

75. Berberian AG, Gonzalez DJX, Cushing LJ. Racial disparities in climate change-related health effects in the United States. *Curr Environ Health Rep*. 2022;9(3):451-464. doi:10.1007/s40572-022-00360-w

76. Buysse CE, Kaulfus A, Nair U, Jaffe DA. Relationships between particulate matter, ozone, and nitrogen oxides during urban smoke events in the western US. *Environ Sci Technol*. 2019;53(21):12519-12528. doi:10.1021/acs.est.9b05241

77. Kalashnikov DA, Schnell JL, Abatzoglou JT, Swain DL, Singh D. Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Sci Adv*. 2022;8(1):eabi9386. doi:10.1126/sciadv.abi9386