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The temporal trend and disparity in short-term health impacts of fine particulate matter in California (2006–2019)

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HIGHLIGHTS

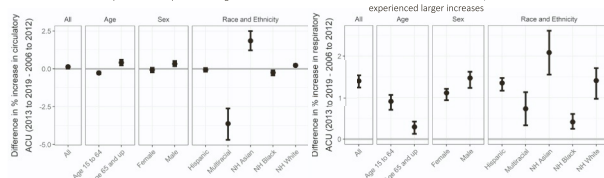
- PM_{2.5} exposure increases California circulatory/respiratory acute care utilization.
- The associations differ by age, sex, race/ethnicity and extreme wildfire exposure.
- The associations increased (2006–2019) with varying changes across subpopulations.

GRAPHICAL ABSTRACT

Objectives:

1. To explore whether temporal trends exist in the relationships between daily PM_{2.5} exposure and circulatory and respiratory acute care utilization in the general population of California from 2006 to 2019
2. To examine for effect modification by age group, sex, race/ethnicity, and extreme wildfire exposure

- ↑ PM_{2.5} exposure → ↑ circulatory acute care utilization, which increased over time
- Older adults, non-Hispanic Asian residents, Hispanic residents, and residents of other and multiracial groups at greatest risk
- Older adults, males, and residents of non-Hispanic Asian and non-Hispanic white experienced larger increases
- ↑ PM_{2.5} exposure → ↑ respiratory acute care utilization, which increased over time
- Females, non-Hispanic Asian residents, and Hispanic residents as well as those not exposed to extreme wildfire at greatest risk
- Younger adults, males, and residents of non-Hispanic Asian as well as those not exposed to extreme wildfire experienced larger increases



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ABSTRACT

Most epidemiological studies assume that the relationship between short-term air pollution exposure and health outcomes is constant over time, which ignores potential changes in population composition and particulate matter emission sources. Limited studies have assessed changes in the relationship between fine particulate matter (PM_{2.5}) and adverse health outcomes over time, with mixed results. Additionally, there is a need to identify which subgroups are disproportionately impacted over time by PM_{2.5}-related health consequences. Therefore, we aimed to examine whether temporal trends exist in the relationships between daily PM_{2.5} exposure and circulatory and respiratory acute care utilization in California from 2006 to 2019. We further assessed whether certain subpopulations are more susceptible to PM_{2.5} exposure by demographic characteristics and extreme wildfire frequency. Daily PM_{2.5} concentrations estimated from a stacked ensemble model and daily cause-specific acute care utilization and demographic data from the California Department of Health Care Access and Information. We analyzed this relationship using modified two-stage Bayesian hierarchical models, where we first did not consider temporal trends, then stratified by two periods, and finally flexibly considered non-linear changes over time. Increases in circulatory (0.56 %; 95 % credible interval (CI): 0.17 %, 0.96 %) and

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respiratory acute care utilization risk (2.61 %; 95%CI: 2.29 %, 2.94 %) were found with every 10 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ on the same day and previous two days. These risks were found to increase over time, where 0.13 % (95%CI: 0.02 %, 0.22 %) and 1.40 % (95%CI: 1.24 %, 1.54 %) increases were identified for circulatory and respiratory acute care utilizations, respectively, from the first (2006–2012) to second period (2013–2019). Differences by age, sex, race/ethnicity, and extreme wildfire frequency were noted. These findings confirm that air pollution guidelines should consider the dynamic nature of epidemiological dose-response and can provide insight for targeted air pollution control and adaptation policies designed to reduce $\text{PM}_{2.5}$ exposure, particularly for the most susceptible subpopulations.

1. Introduction

Short-term exposure to fine particulate matter ($\text{PM}_{2.5}$) has been consistently linked to increased morbidity and mortality across different populations (Di et al., 2017; Dominici et al., 2006; Tian et al., 2019; Zanobetti and Schwartz, 2009). Being a complex mixture produced by various anthropogenic and natural activities, the composition of $\text{PM}_{2.5}$ has demonstrated spatial and temporal heterogeneity, which could lead to variations in $\text{PM}_{2.5}$ -related health risk (Atkinson et al., 2015; Bell et al., 2007, 2014; Krall et al., 2013; Levy et al., 2012). Additionally, changes in population composition over time contribute to shifts in susceptibility, warranting the need to study the relationship between $\text{PM}_{2.5}$ exposure and adverse health outcomes over time. Previous studies have found evidence supporting changes in the association between short-term exposure to particulate matter and mortality (Breitner et al., 2009; Carugno et al., 2017; Choi et al., 2018; Dominici et al., 2007; Kim et al., 2015), cardiovascular hospitalizations (Bi et al., 2020), and respiratory hospitalizations (Chen et al., 2021; Kim et al., 2017). Many of these studies identified an overall decrease or a period of increase followed by a recent decline in the temporal trend of $\text{PM}_{2.5}$ -related health risks with some spatial and temporal heterogeneity, with the exception of three studies that identified general increases over time for cardiovascular emergency department visits in Los Angeles, U.S. (Bi et al., 2020), asthma hospitalizations and mortality in Seoul, Korea (Kim et al., 2015; Kim et al., 2017).

Moreover, certain subpopulations have been shown to be more vulnerable to short-term $\text{PM}_{2.5}$ -related health impacts, highlighting the need for equitable solutions to reduce this health burden. Susceptible subpopulations include but are not limited to older adults, marginalized racial and ethnic groups, and women, who are at greater risk for cardiovascular and respiratory hospitalizations and death after short-term exposure to $\text{PM}_{2.5}$ (Bell et al., 2013, 2015; Chen et al., 2018, 2022; Ebisu et al., 2019; Hicken et al., 2023; J. C. Liu et al., 2017; Mehta et al., 2021). Certain neighborhoods are also exposed to greater levels of $\text{PM}_{2.5}$ as a legacy of racist land use planning, such as more populated areas and those with greater proportions of lower-income, Hispanic, Asian, and Black individuals (Collins et al., 2022; Jbaily et al., 2022; Jones et al., 2014; J. Liu et al., 2021), and many of these areas have remained highly exposed despite national $\text{PM}_{2.5}$ levels decreasing over time (Brigham and Crocker, 2024; Colmer et al., 2020; Kravitz-Wirtz et al., 2016; Ma et al., 2023). Despite changes in population composition and behavior patterns over time, few studies have assessed temporal changes in the impacts of $\text{PM}_{2.5}$ exposure on health outcomes in specific subpopulations. Bi et al. (2020) found similar temporal patterns of association between acute $\text{PM}_{2.5}$ exposure and the risk of cardiovascular emergency department visits across age groups in California from 2005 to 2016. Chen et al. (2022) found larger increases in associations between acute $\text{PM}_{2.5}$ exposure and risk of cardiovascular hospitalizations among poorer, older, and male individuals, and smaller decreases for respiratory hospitalizations among poorer and male individuals, which were more pronounced in 2013 to 2016. However, previous studies either concentrated on a narrow geographical area (i.e. Los Angeles County) (Bi et al., 2020) or on the elderly subpopulation only, warranting a study focusing on the general population with broader geographical coverage (Chen et al., 2022). Subpopulation-specific

concentration-response functions and their temporal variation are important to examine for accurate health impact assessments that do not underestimate the impacts on susceptible subgroups (Spiller et al., 2021). These can be rendered into tailored equitable interventions and policies aimed at reducing the health burden in the most affected populations.

Increasing wildfire activities is one important factor to explore among characteristics affecting the temporal trend of $\text{PM}_{2.5}$ -related health impacts (Rappold et al., 2017). In the United States between 2008 and 2012, approximately 30.5 million individuals were estimated to reside in areas with a high $\text{PM}_{2.5}$ contribution from wildfires ($>1.5 \mu\text{g}/\text{m}^3$), and 10.3 million individuals were exposed to high levels of $\text{PM}_{2.5}$ from wildfire smoke for >10 days annually (Rappold et al., 2017). An increasing number of individuals are additionally expected to live in areas exposed to wildfire activities in the future as climate change progresses (Burke et al., 2021; Ford et al., 2018; Goss et al., 2020; A. L. Westerling et al., 2006; A. L. Westerling and Bryant, 2007; Williams et al., 2019). Wildfire-related $\text{PM}_{2.5}$ exposure is associated with an increased risk of mortality (Matz et al., 2020) as well as cardiovascular and respiratory hospitalization (Aguilera et al., 2021; Haikerwal et al., 2015; Yao et al., 2013; Youssof et al., 2014). Studies have identified that wildfire-related $\text{PM}_{2.5}$ contained more toxic chemical components to the lungs than $\text{PM}_{2.5}$ without wildfire exposure as a result of oxidative stress (Stowell et al., 2019; Wegesser et al., 2009). Aguilera and colleagues (2021) also found evidence supporting higher $\text{PM}_{2.5}$ -respiratory hospitalization association with wildfire-related $\text{PM}_{2.5}$ than with non-wildfire $\text{PM}_{2.5}$. This underscores the need to study the adverse health impacts of wildfire-specific $\text{PM}_{2.5}$ especially in the context of climate change, where wildfires will become more frequent and intense due to climate change (A. L. Westerling and Bryant, 2007; Williams et al., 2019). Despite this, it is unclear whether changes in wildfire prevalence contributed to changes in $\text{PM}_{2.5}$ -health association over time.

In California, a state with a diverse population, changes in the source of $\text{PM}_{2.5}$ has occurred over time as a result of regulations as well as wildfires, providing a chance to study temporal changes in the impact of $\text{PM}_{2.5}$ -related health risks (Karmel et al., 2002; Lurmann et al., 2015). While emission reduction policies have been implemented in the state, wildfire activity and annual burned area has grown significantly since the early 1970's, leading to a higher proportion of $\text{PM}_{2.5}$ attributable to wildfire over time (Burke et al., 2021; Reid et al., 2016; A. L. Westerling et al., 2006; A. L. Westerling and Bryant, 2007; Anthony Leroy Westerling, 2018; Williams et al., 2019). A previous study has found an increase in $\text{PM}_{2.5}$ -related risk of cardiovascular emergency department visits in Los Angeles from the period of 2005 to 2008, to later periods until 2016, without exploring its connection with wildfire (Bi et al., 2020). Better understanding the temporal trends of the $\text{PM}_{2.5}$ -health association could aid in designing targeted air pollution control and adaptation policies in areas based on whether they are prone to wildfire prevalence as well as based on the proportion of vulnerable subgroups.

In this study, we explored whether temporal trends exist in the relationships between $\text{PM}_{2.5}$ exposure and circulatory and respiratory acute care utilization in the general population of California from 2006 to 2019. We additionally examined whether any disparities exist in the temporal trends by age group, sex, and race/ethnicity. We then assessed effect modification of this $\text{PM}_{2.5}$ -acute care utilization relationship by

exposure to extreme wildfire. Taken together, this analysis provides an accurate and comprehensive risk assessment while identifying sub-populations with the greatest PM_{2.5}-related health risk, especially for those impacted by widening disparities.

2. Material and methods

2.1. Data sources and study population

We assembled a daily time-series dataset of cause-specific acute care utilization, PM_{2.5} concentrations, and meteorological conditions in California ZIP Code Tabulation Areas (ZCTA) from 2006 to 2019 to explore the disparities and temporal trend in acute health impacts of ambient PM_{2.5}. We restricted our analyses to 192 ZCTAs satisfying two criteria to ensure sufficient statistical power for time-varying analyses: 1) having a total population of $\geq 50,000$ in the 2010 U.S. Decennial Census (Decennial Census of Population and Housing Datasets, 2021); and 2) having at least 50 % of days with complete health, PM_{2.5}, and meteorological data for every year in the study period.

2.1.1. Exposure data

We utilized a previously developed time-series dataset for ZCTA-level daily total PM_{2.5} concentrations in California from 2006 to 2019 (Aguilera et al., 2023). Aguilera et al. (2023) generated the ZCTA-level daily total PM_{2.5} concentrations using a stacked ensemble model with data-adaptive algorithms (e.g., deep learning, distributed random forest, and gradient boosting) and predictors such as air monitor data, satellite-derived aerosol properties, meteorological conditions, and land-use information. The estimates achieved a prediction R² of 0.78 in the held-out test set of five representative monitors in California and demonstrated high agreement with PM_{2.5} estimates obtained by Di et al. (2019) and Reid et al. (2021) (correlations of 0.78 and 0.73).

2.1.2. Health outcomes

We obtained daily cause-specific acute care utilization data and demographic characteristics recorded during the medical visit from the California Department of Health Care Access and Information (formerly known as the Office of Statewide Health Planning and Development) to create a dataset for ZIP code-level age group- (0 to 14 years, 15 to 64 years, and 65 years old and up), sex- (female and male), and race/ethnicity- (Hispanic, non-Hispanic Asian, non-Hispanic Black, non-Hispanic Native, non-Hispanic white, and other) specific daily number of acute care utilization (California Department of Health Care Access and Information, 2024). The non-Hispanic Asian group contains non-Hispanic Asian, Pacific Islander, Native Hawaiian, and other Pacific Islander. The non-Hispanic Native group contains Native American, Eskimo, and Aleut. The other group contains people with a racial group recorded as other than those described before or as multiracial. Combining the Patient Discharge Data and the Emergency Department Data, this dataset contained all acute care utilizations that were not prearranged in the general population of California, including unscheduled hospitalizations and emergency department visits. In this dataset, emergency department visits leading to hospitalizations were only recorded as unscheduled hospitalizations. For each ZIP code, we identified circulatory and respiratory acute care utilizations based on their primary diagnosis codes recorded (see the list of *International Classification of Diseases* codes included for either type of acute care utilizations in Appendix 1). We identified the ZIP code of each acute care utilization based on the patient's residential address at the time of the visit. Since the ZCTAs represent populated areas of the ZIP code service area, we treated them the same in analysis and refer to them as ZCTAs in the remainder of this manuscript. We also obtained age group-, sex-, and race/ethnicity-specific population sizes for each ZCTA from the 2010 U.S. Decennial Census as the population at risk used in the statistical model (Decennial Census of Population and Housing Datasets, 2021).

2.1.3. Meteorological data and extreme wildfire frequency

Since meteorological conditions like ambient temperature and humidity could affect the formation of secondary PM_{2.5} in the atmosphere, and health outcomes (Green et al., 2019; Song et al., 2017), we calculated daily ZCTA-specific temperature and dew point temperature by extracting the daily value from the grid cell of the existing 4 km \times 4 km surfaces of Parameter-elevation Relationships on Independent Slopes Model AN81d version D2 dataset in which the ZCTA population center falls (PRISM Climate Group, 2021).

Additionally, the ZCTA-level daily wildfire-specific PM_{2.5} was previously created by imputing non-wildfire PM_{2.5} concentrations in ZCTA-days exposed to smoke plume and subtracting the value from estimated total PM_{2.5} concentrations (Aguilera et al., 2023). We dichotomized the 192 ZCTAs into two extreme wildfire exposure groups: one with some days in the study period exposed to wildfire-specific PM_{2.5} higher than 35 $\mu\text{g}/\text{m}^3$ and the other without such days (Aguilera et al., 2023). 35 $\mu\text{g}/\text{m}^3$ was selected as the extreme wildfire cut point, as it is the US Environmental Protection Agency's 24-h standard for PM_{2.5} from all sources (NAAQS Table, 2024).

2.2. Statistical analysis

We analyzed the time-series dataset using a modified two-stage Bayesian hierarchical model described previously (Chen et al., 2021, 2022). Specifically, in the base model for each ZCTA, we evaluated the association between daily PM_{2.5} concentration and risk of acute care utilization in the same day with a quasi-Poisson model, including an offset term for the ZCTA-specific population at risk, day of week, natural cubic spline function of the same-day temperature and dew point temperature with three degrees of freedom, natural cubic spline function of the previous three days' average temperature and dew point temperature with three degrees of freedom, and a natural cubic spline function of time with 13 degrees of freedom per year. We adjusted for both same-day and previous three days' average meteorological conditions because the influence of such conditions on PM_{2.5} and health outcomes might extend beyond one day, which has been frequently considered in the literature (R. Chen et al., 2017; Li et al., 2018; Lin et al., 2017a, 2017b; Zhang et al., 2019). The last variable for time could account for any long-term changes beyond a month in the count of acute care utilization, such as population size changes and seasonal influenza peaks. Although previous studies identified 8–12 degrees of freedom per year in the natural cubic spline function of time as sufficient for long-term and seasonal trend adjustment (Dominici et al., 2006; Peng et al., 2006), our sensitivity analyses showed that more aggressive smoothing is needed to obtain stable estimates, especially for later years and respiratory acute care utilization (Fig. A.1). We chose the moving average of PM_{2.5} concentration in the same day and previous two days as the main exposure of interest as this exposure metric will likely capture the health impact of PM_{2.5} more fully than a single-day lag model while remaining parsimonious (Chen et al., 2022). We also explored the association between daily PM_{2.5} and the risk of acute care utilization in the next two days by running single-day lag models up to two days after the exposure separately. We then pooled ZCTA-specific estimates from the quasi-Poisson model to obtain an overall estimate or extreme wildfire group-specific estimates in the second stage.

In the stratification analysis, we employed the base model described above after stratifying the dataset into the 2006 to 2012 period and the 2013 to 2019 period, which were chosen to achieve same length of years in each stratum. Additionally, we opted to stratify the data to two periods for facilitated interpretability of the temporal trend of the PM_{2.5}-health relationship. We then calculated the change in the association across periods to represent the temporal trend. To allow the association between daily PM_{2.5} concentration and risk of acute care utilization to change over time, we incorporated an interaction between daily PM_{2.5} concentration and a natural cubic spline function of year with 4 internal knots at quantiles (non-linear model).

To evaluate effect modification by age group, sex, and race/ethnicity, we stratified the outcomes by these demographics and conducted the analysis for each subgroup separately. We also conducted heterogeneity tests across subgroups using Cochran’s Q test to evaluate whether the association and change in association across periods differ across subgroups using a significance criterion of 0.1 given the lower power of the test (Kaufman and MacLehose, 2013).

We presented associations as percentage increases in risk of acute care utilization per 10 µg/m³ increase in daily PM_{2.5} concentration. We calculated 95 % posterior credible intervals using the 2.5th and 97.5th percentile of a random sample of 10,000 from the posterior distribution. All analyses were done in R version 4.1.0 (R Core Team, 2021) with R studio (Posit team., 2023), “tsModel” package, and “tlnise” package (Everson and Morris, 2000; Peng, 2022). The analytical code can be found in our GitHub repository with a mock dataset to facilitate replication.

3. Results

3.1. Study population characteristics

Among 12,306,150 individuals (33 % of the population in California) of the 192 ZCTAs included in this study (Fig. A.2), we observed 2,755,639 (0.44 per 10,000 person-days) and 6,669,549 (1.06 per 10,000 person-days) circulatory and respiratory acute care utilizations from 2006 to 2019, respectively (Table 1). Those 65 years and older accounted for 9.4 % of the population and experienced about half of the circulatory acute care utilizations, while those 0 to 14 years accounted for 22.6 % of the population and experienced about half of the respiratory acute care utilizations. Compared to females, males experienced a higher rate of circulatory acute care utilizations and a lower rate of respiratory acute care utilizations. Hispanics consist of 50.4 % of the study population, followed by non-Hispanic white, non-Hispanic Asian, non-Hispanic Black, non-Hispanic races other than those explicitly listed or multiracial, and non-Hispanic Native. Non-Hispanic white individuals experienced the highest number of circulatory acute care utilizations, followed by Hispanic, non-Hispanic Black, non-Hispanic Asian, non-Hispanic races other than those explicitly listed or multiracial, and non-Hispanic Native. In contrast, Hispanic experienced the highest number of respiratory acute care utilizations, followed by non-

Hispanic white, non-Hispanic Black, non-Hispanic Asian, races other than those explicitly listed or multiracial, and non-Hispanic Native. Acute care utilizations among people with unknown age group, sex, or race/ethnicity consisted of <2 % of the total utilizations and such categories were omitted in subgroup analyses. The number of acute care utilizations increased from 2006 to 2019 for both causes of utilization and all subgroups except for non-Hispanic white individuals.

The median ZCTA-specific annual average PM_{2.5} concentration decreased from 14.0 µg/m³ (1st and 3rd quantiles: 11.0 and 16.4 µg/m³, respectively) in 2006 to 9.5 µg/m³ (1st and 3rd quantiles: 7.5 and 11.1 µg/m³, respectively) in 2019. The median ZCTA-specific total number of days with wildfire-specific PM_{2.5} concentration higher than 35 µg/m³ from 2006 to 2019 is 1 (minimum and maximum: 0 and 26), while 101 ZCTAs did not experience such intensive daily wildfire-specific PM_{2.5} levels (Fig. A.2).

3.2. Base model not considering temporal trends

Assuming no change in association across time, we observed a 0.56 % (95 % credible interval (CI): 0.17 %, 0.96 %) increase in circulatory acute care utilization per 10 µg/m³ increase in the moving average of PM_{2.5} concentration in the same day and previous two days (Table A.1). We observed heterogeneous associations by age and race/ethnicity (Table A.1). Subpopulations that experienced higher associations were those aged 65 and up, non-Hispanic Asian residents, Hispanic residents, and residents of race/ethnicity other than those explicitly described (i. e., other than white, Asian, Black, Native, and Hispanic) or multiracial (Fig. 1A). ZCTAs with and without days in the study period exposed to wildfire-specific PM_{2.5} higher than 35 µg/m³ experienced similar associations between PM_{2.5} and circulatory acute care utilization (Fig. A.3 A and Table A.1).

We also observed a 2.61 % (95 % CI: 2.29 %, 2.94 %) increase in respiratory acute care utilization per 10 µg/m³ increase in the moving average of PM_{2.5} concentration in the same day and previous two days, with heterogeneous associations observed by sex and borderline heterogeneous associations across race/ethnicity (Table A.1). Subpopulations that experienced higher associations were females, non-Hispanic Asian residents, and Hispanic residents (Fig. 1B). ZCTAs with days in the study period exposed to wildfire-specific PM_{2.5} higher than 35 µg/m³ experienced lower associations between PM_{2.5} and respiratory

Table 1
Summary of study population and acute care utilizations by sex, age group, and race/ethnicity.

Population	Population size (% of total)	Circulatory acute care utilization (rate per 100,000 person-day)			Respiratory acute care utilization (rate per 100,000 person-day)		
		Entire study period	Start year (2006)	Final year (2019)	Entire study period	Start year (2006)	Final year (2019)
Total population	12,306,150 (100)	2,755,639 (4.4)	178,213 (4.0)	230,586 (5.1)	6,669,549 (10.6)	373,264 (8.4)	515,010 (11.5)
Age group							
0 to 14 years	2,785,418 (22.6)	27,771 (0.2)	1564 (0.2)	3100 (0.3)	2,976,475 (20.9)	169,720 (16.8)	218,915 (21.5)
15 to 64 years	8,365,008 (68.0)	1,323,631 (3.1)	82,453 (2.7)	108,303 (3.5)	2,829,336 (6.6)	147,207 (4.9)	228,242 (7.5)
65 years old and up	1,155,724 (9.4)	1,404,221 (23.8)	94,190 (2 _{2.5})	119,181 (28.3)	863,716 (14.6)	56,337 (13.5)	67,850 (16.1)
Unknown ⁺	NA	16 (NA)	6 (NA)	2 (NA)	22 (NA)	0 (NA)	3(NA)
Sex							
Female	6,182,465 (50.2)	13,45,943 (4.3)	89,386 (4.0)	110,138 (4.9)	3,498,401 (11.1)	193,394 (8.6)	272,229 (12.1)
Male	6,123,685 (49.8)	1,409,586 (4.5)	88,818 (4.0)	120,430 (5.4)	3,170,942 (10.1)	179,828 (8.1)	242,765 (10.9)
Unknown ⁺	NA	110 (NA)	9 (NA)	18 (NA)	206 (NA)	42 (NA)	16 (NA)
Race/ethnicity							
Hispanic	6,197,758 (50.4)	887,083 (2.8)	48,718 (2.2)	84,046 (3.7)	3,441,137 (10.9)	165,671 (7.4)	286,684 (12.7)
Non-Hispanic Asian	1,701,590 (13.8)	280,058 (3.2)	15,627 (2.5)	25,969 (4.2)	375,664 (4.3)	18,959 (3.1)	32,192 (5.2)
Non-Hispanic Black	790,391 (6.4)	349,496 (8.7)	22,159 (7.7)	27,747 (9.6)	849,902 (21.0)	46,842 (16.4)	61,629 (21.4)
Non -Hispanic Native	37,596 (0.3)	5247 (2.7)	294 (2.2)	428 (3.1)	11,173 (5.8)	676 (5.0)	827 (6.0)
Non -Hispanic white	3,281,283 (26.7)	1,101,375 (6.6)	80,636 (6.8)	79,966 (6.7)	1,622,798 (9.7)	109,739 (9.2)	103,637 (8.7)
Other races than above or multiracial	297,532 (2.4)	99,724 (6.6)	5620 (5.2)	11,335 (10.4)	267,135 (17.6)	16,112 (15.0)	27,773 (25.6)
Unknown ⁺	NA	32,656 (NA)	5159 (NA)	1095 (NA)	101,740 (NA)	15,265 (NA)	2268 (NA)

⁺ The acute care utilization data includes unknown category for age group, sex and race/ethnicity, which has no corresponding categories in the 2010 US Decennial Census reported population sizes.

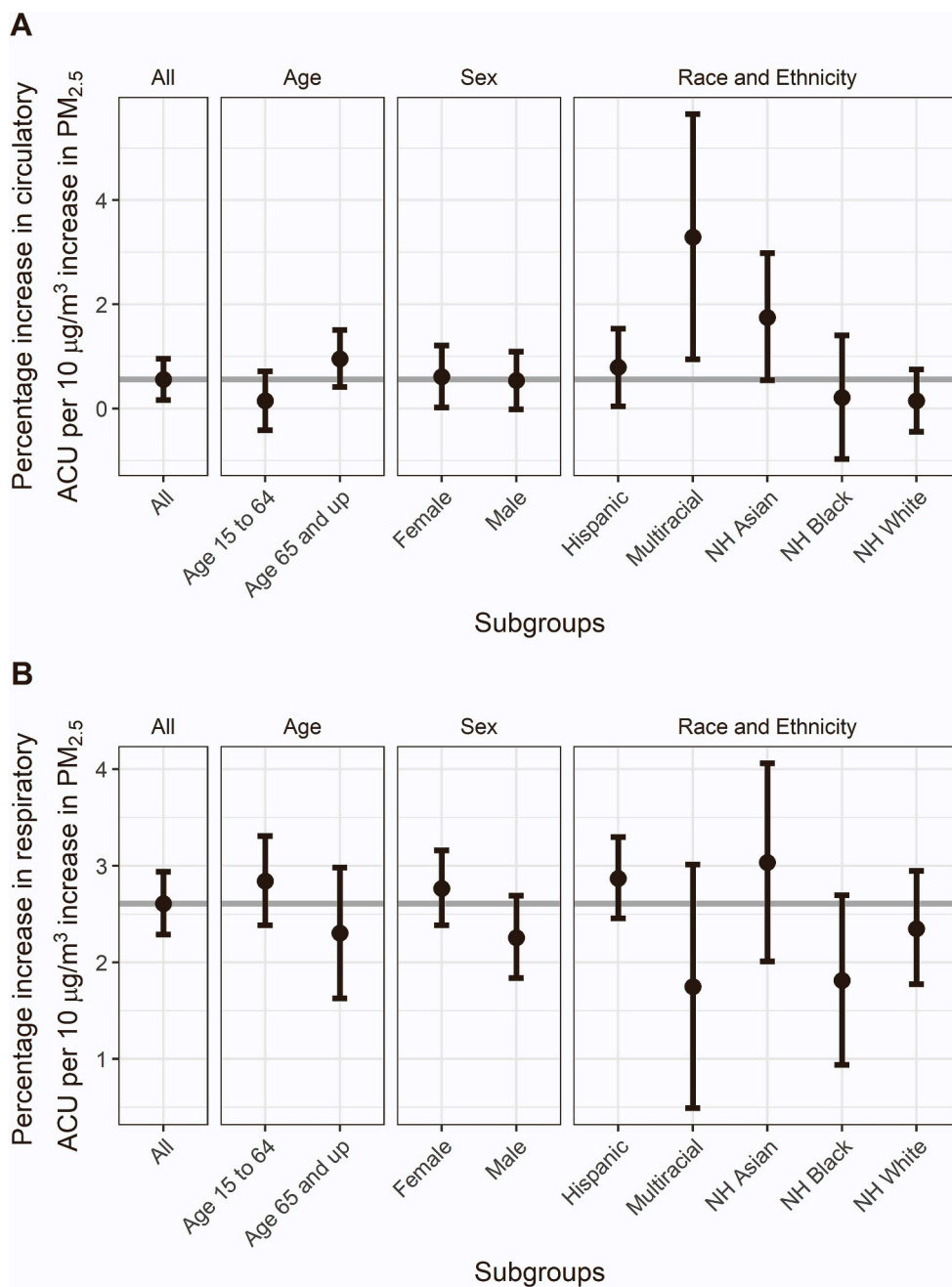


Fig. 1. The association between moving average of $\text{PM}_{2.5}$ concentration in same day and previous two days and risk of acute care utilizations (ACUs) by cause and subgroup using the basic model not considering temporal trend. Gray line represents the association in the total population. Note: age 0 to 14 subgroup and non-Hispanic Native American subgroup were emitted due to small population size and first-stage model convergence failures in more than half of the included ZCTAs. Results for non-Hispanic Asian, non-Hispanic Black, and other races than above or multiracial are based on 161, 159 and 141 ZCTAs due to failure to converge in some ZCTAs.

acute care utilization compared to ZCTAs without such days (Fig. A.3B and Table A.1).

The association between single-day $\text{PM}_{2.5}$ exposure and the risk of acute care utilization decreased from the same day to two days after the exposure, with most of the effect captured by the same-day health outcome, especially for circulatory outcomes (Fig. A.4). The $\text{PM}_{2.5}$ -health associations were also similar for exposure based on the moving average of the same-day and previous two days and exposure based on the moving average of the same-day and previous day, while both associations were higher than single-day estimates (Fig. A.4).

3.3. Period-stratified base model

After stratifying the study into two periods, 2006–2012 and 2013–2019, we observed a 0.13 % (95 % CI: 0.02 %, 0.22 %) increase in the association between $\text{PM}_{2.5}$ concentration and the risk of circulatory acute care utilization from the first to the second period (Fig. 2A and Table A.2), while the associations remained positive in both periods (Fig. A.5 A). The changes were different by age, sex, and race/ethnicity (Table A.2). Subpopulations that experienced larger increases in associations are those aged 65 and up, males, non-Hispanic Asian residents, and non-Hispanic white residents (Fig. 2A). ZCTAs with and without days in the study period exposed to wildfire-specific $\text{PM}_{2.5}$ higher than

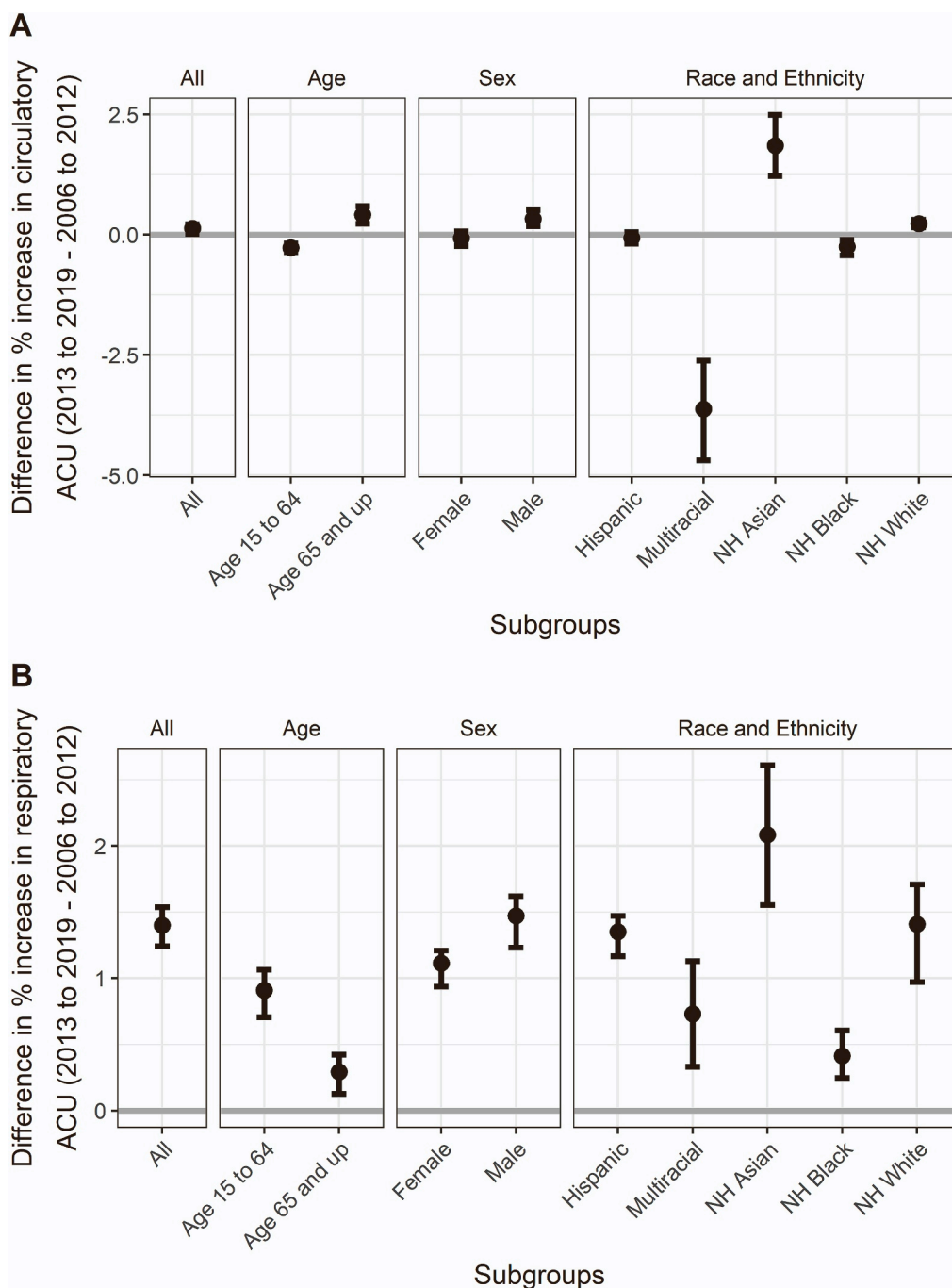


Fig. 2. The difference in associations between moving average of PM_{2.5} concentration in same day and previous two days and risk of acute care utilizations by cause, subgroup and study period using the basic model stratified into two periods. Gray line represents no change in the association. Note: age 0 to 14 subgroup and non-Hispanic Native American subgroup were emitted due to small population size and first-stage model convergence failures in more than half of the included ZCTAs. Results for non-Hispanic Asian, non-Hispanic Black, and other races than above or multiracial are based on 161, 159 and 141 ZCTAs due to failure to convergence in some ZCTAs.

35 µg/m³ experienced similar changes in associations of PM_{2.5} and circulatory acute care utilization (Table A.2 and Fig. A.3 A).

We also observed a 1.40 % (95 % CI: 1.24 %, 1.54 %) increase in the association between PM_{2.5} concentration and the risk of respiratory acute care utilization from the first to the second period (Fig. 2B and Table A.2), while the associations remained positive in both periods (Fig. A.5B). The changes were different by age, sex, and race/ethnicity (Table A.2). Subpopulations that experienced larger increases in associations are those aged 15 to 64 years, males, and non-Hispanic Asian residents (Fig. 2B). ZCTAs with days in the study period exposed to

wildfire-specific PM_{2.5} higher than 35 µg/m³ experienced lower increases in associations of PM_{2.5} and respiratory acute care utilization than ZCTAs without such intense wildfire smoke days (Table A.2 and Fig. A.3B).

3.4. Non-linear model

When allowing the associations between PM_{2.5} and circulatory acute care utilization to vary non-linearly over time, we observed an increase in the association over the study period for the entire population

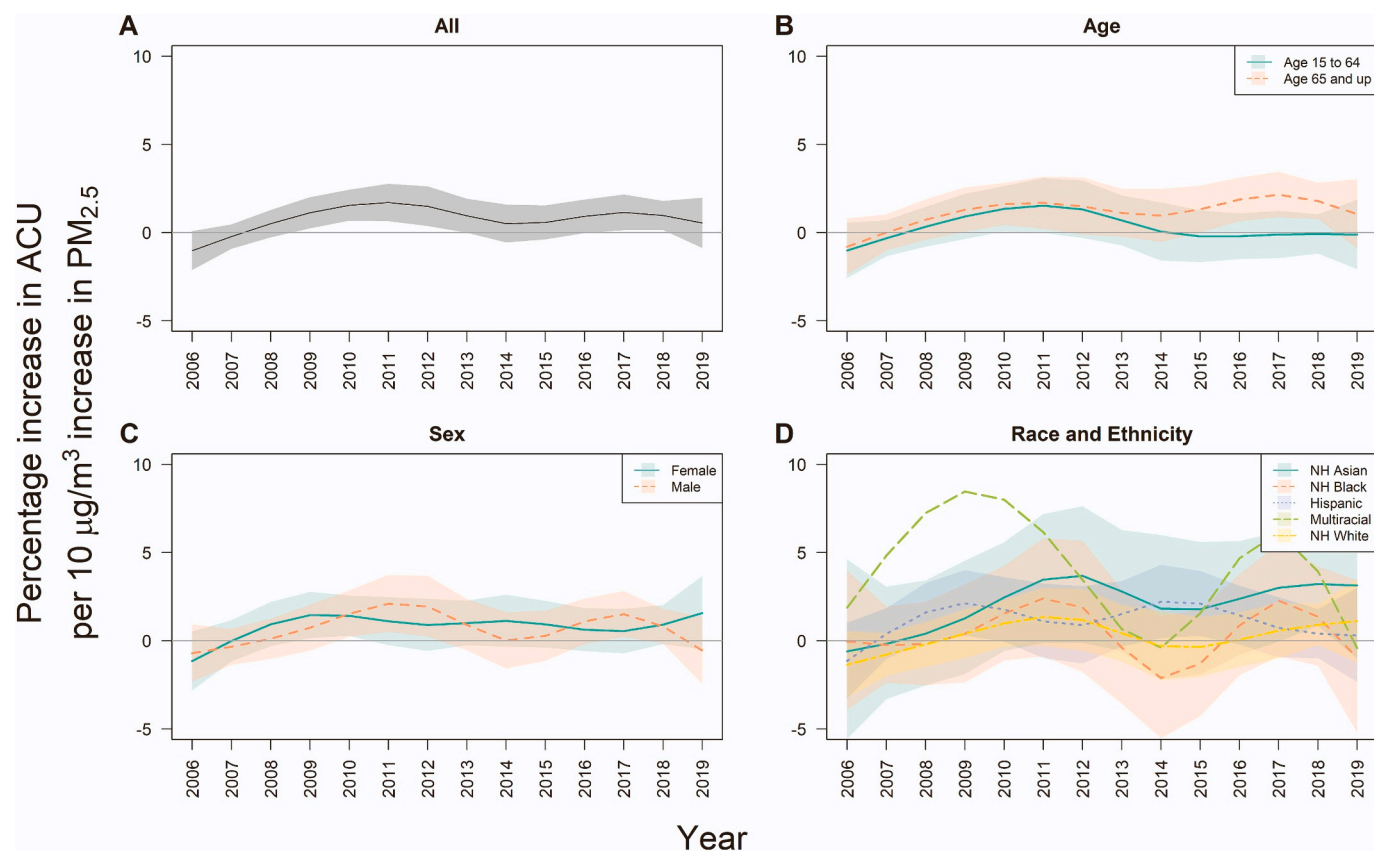


Fig. 3. The association between moving average of PM_{2.5} concentration in same day and previous two days and risk of circulatory acute care utilizations by subgroup using the non-linear temporal model. A: general population; B: stratified by age group; C: stratified by sex; D: stratified by race and ethnicity. Note: age 0 to 14 subgroup and non-Hispanic Native American subgroup were emitted due to small population size and first-stage model convergence failures in more than half of the included ZCTAs. Results for non-Hispanic Asian, non-Hispanic Black, and other races than above or multiracial are based on 163, 163 and 152 ZCTAs due to failure to convergence in some ZCTAs.

(Fig. 3A). We observed increases for those aged 65 and up from 2014 to 2019 when compared to those 15 to 64 years old (Fig. 3B). The temporal trends for both sexes fluctuated over time without a clear pattern (Fig. 3C). Non-Hispanic Asian residents tended to experience higher associations, with the exception of the multiracial and other race/ethnic group from 2010 to 2012 and 2015–2018, from 2010 and on (Fig. 3D). ZCTAs without days in the study period exposed to wildfire-specific PM_{2.5} higher than 35 µg/m³ experienced higher associations from 2014 to 2019 when compared to ZCTAs with such intense wildfire smoke days, with overlapping credible intervals (Fig. A.6 A).

When allowing the associations between PM_{2.5} and respiratory acute care utilization to vary non-linearly over time, we observed a fluctuating but overall increasing trend in the association over the study period for the entire population, with a peak between 2016 and 2018 (Fig. 4A). Those aged 15 to 64 experienced an increase in associations from 2017 to 2019 when compared to those aged 65 and up (Fig. 4B). We did not observe differences by sex in the temporal trends of associations (Fig. 4C). Non-Hispanic Asian residents experienced higher associations than all other racial and ethnic groups from 2012 and on (Fig. 4D). ZCTAs without days in the study period exposed to wildfire-specific PM_{2.5} higher than 35 µg/m³ experienced higher associations from 2006 to 2011 and from 2014 to 2019 when compared to ZCTAs with such intense wildfire smoke days (Fig. A.6B).

4. Discussion

In California, we identified a harmful effect of ambient daily PM_{2.5} on the risk of both circulatory and respiratory acute care utilization from 2006 to 2019, assuming constant associations over time. Additionally,

we observed an overall increase in the associations between the risk of both circulatory and respiratory acute care utilization and short-term exposure to PM_{2.5} when stratifying the study into two periods (2006–2012 and 2013–2019) as well as when allowing the PM_{2.5}-acute care utilization relationship to vary nonlinearly over time.

Most studies have identified a positive relationship between short-term PM_{2.5} exposure and adverse health outcomes; however, previous results about the temporal trend in this relationship across geographic regions and time periods were mixed. For instance, the impact of PM_{2.5} on mortality decreased in most Iranian cities from 2013 to 2016 (Hopke et al., 2018). Similarly, in Erfurt, Germany, from 1995 to 2002, the risk ratios between 6-day average PM_{2.5} exposure and mortality decreased (Breitner et al., 2009). In Seoul, Korea, the association between PM_{2.5} exposure and asthma hospitalizations also decreased from 2003 to 2011 (Kim et al., 2017). In contrast, Kim et al. (2015) found that the association between PM_{2.5} exposure and all-cause mortality increased from 2002 to 2006 to 2007–2011 in Seoul, Korea. In Los Angeles, California, Bi et al. (2020) identified differing temporal trends depending on the health outcome assessed, where an increase in PM_{2.5} exposure led to a greater risk in cardiovascular emergency department visits in a later period (2013–2016) than an earlier period (2005–2008), while a lower risk in asthma emergency department visits were identified in the later period than the earlier period. Our study provided evidence that an increasing temporal trend existed in the impacts of PM_{2.5} exposure on adverse health outcomes for the general population in California from 2006 to 2019, which should be considered in evaluation of health burden and development of interventions.

As pointed out by previous studies (Bi et al., 2020; Chen et al., 2022; Dominici et al., 2007), the observed temporal trends in the association

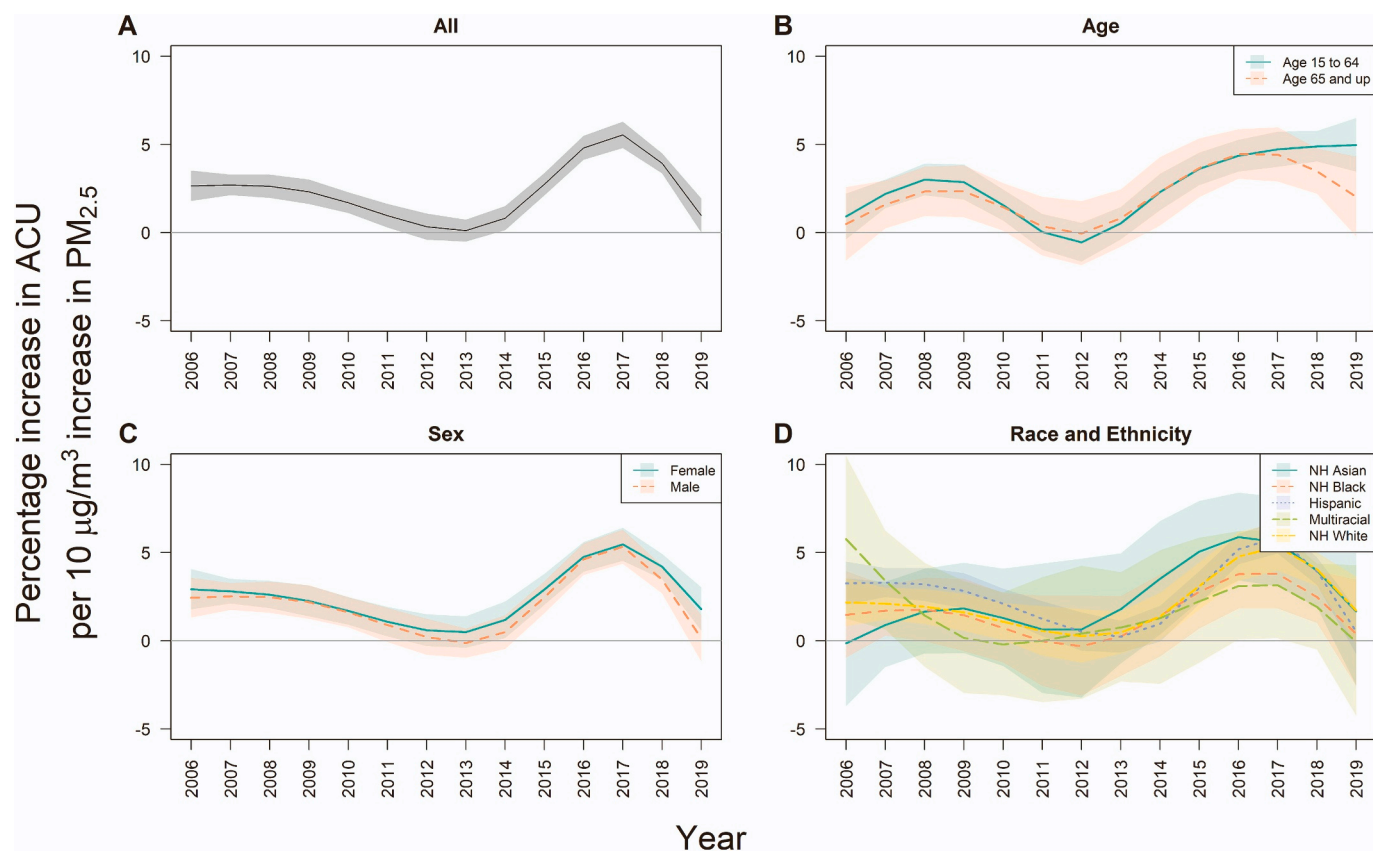


Fig. 4. The association between moving average of PM_{2.5} concentration in same day and previous two days and risk of respiratory acute care utilizations by subgroup using the non-linear temporal model. A: general population; B: stratified by age group; C: stratified by sex; D: stratified by race and ethnicity. Note: age 0 to 14 subgroup and non-Hispanic Native American subgroup were emitted due to small population size and first-stage model convergence failures in more than half of the included ZCTAs. Results for non-Hispanic Asian, non-Hispanic Black, and other races than above or multiracial are based on 163, 163 and 152 ZCTAs due to failure to convergence in some ZCTAs.

between short-term exposure to PM_{2.5} and adverse health outcomes could originate from changes in multiple factors, including sources of PM_{2.5} and corresponding PM_{2.5} composition, and population susceptibility. For example, the observed temporal trend demonstrated a more pronounced increase in 2009–2013 and 2016–2018, which coincided with the prevalence of huge wildfires in California ([History of California Wildfires, 2024](#)). As an effort to understand the influence of wildfire sources on the temporal trend, we explored the frequency of intense wildfire smoke as a potential effect modifier and observed higher associations between PM_{2.5} and acute care utilizations among ZCTAs without exposure to intense wildfire smoke in the study period, with more pronounced differences in 2014 to 2019. Although previous studies found higher health impacts from wildfire-specific PM_{2.5} than PM_{2.5} from all sources, our observations are not too surprising since our wildfire metric captured the exposure to intense wildfire smoke during the entire study period ([Aguilera et al., 2020](#)). In fact, all ZCTAs included were exposed to some days with wildfire-specific PM_{2.5} from 2006 to 2019, while fewer than half of them experienced days with intense wildfire smoke (i.e., wildfire-specific PM_{2.5} higher or equal to 35 µg/m³) ([Aguilera et al., 2020](#)). In other words, it is possible that residents in ZCTAs experiencing more intense wildfire smoke events over time might be more aware of the health impacts of wildfire smoke and made behavior changes like closing windows or staying indoor to reduce their exposure in subsequent wildfire smoke events and the corresponding health responses, while those never having experienced such intense wildfire smoke might be less prepared as wildfire frequency increased in recent years. A recent study revealed that behavior and building characteristics could lead to up to 20 times differences in residents' actual exposure to wildfire smoke ([Burke et al., 2022](#)).

Altering population susceptibility could be another factor contributing to the temporal change, potentially due to changes in prevalence of pre-existing conditions, access to health care resources, behavior patterns affecting exposure to ambient PM_{2.5}, and changes in population composition. For example, diabetes prevalence has increased over time and potentially creating more susceptible individuals towards PM_{2.5} ([Taylor et al., 2019](#)). Furthermore, major modifications occurred to health care in California, including the Bridge to Reform waiver in 2010 and the Affordable Care Act implemented in 2014, which improved Medicaid coverage and eligibility as well as Medicare benefits ([Gaffney and McCormick, 2017](#); [Harbage and King, 2012](#); [Kinney, 2013](#)).

Additionally, we observed effect modification by age, race, and sex. With increasing PM_{2.5} exposure, older adults, non-Hispanic Asian residents, Hispanic residents, and residents of other and multiracial groups were at greater risks of circulatory acute care utilization, while females, non-Hispanic Asian residents, and Hispanic residents were at greater risks of respiratory acute care utilization. In parallel, several significant changes occurred to the population composition of California. The population grew by almost 10 %, the proportion of Hispanic, Asian, and non-Hispanic multiracial individuals increased, the proportion of non-Hispanic white individuals decreased, and the proportion of older adults rose (e.g., 50+ years old) ([USAFacts, 2022](#)), potentially driving the observed increases in overall associations between PM_{2.5} and acute care utilizations.

Moreover, the relative risk of PM_{2.5} exposure on acute care utilization has also increased for these high-risk subgroups over time, except for the relatively constant relative risk of circulatory acute care utilization among Hispanic residents. Comparing the temporal trends across all subgroups, we observed widening disparities in PM_{2.5}-health

relationships across age groups and racial and ethnic groups, with higher relative risks of circulatory outcomes among the older adults, higher relative risk of respiratory outcomes among the younger adults, and higher relative risks of both outcomes among the non-Hispanic Asian residents. We did not observe a clear pattern in PM_{2.5}-health relationships across both sexes. Previous studies consistently reported higher PM_{2.5}-health relationship among older adults, marginalized racial and ethnic groups, and women (Bell et al., 2013, 2015; Hicken et al., 2023; J. C. Liu et al., 2017; Mehta et al., 2021), while the few studies considering temporal trends reported larger increases in PM_{2.5}-health relationships among males and older subgroups but no differences across racial and ethnic groups (Bi et al., 2020; Chen et al., 2022). These differences in subgroup-specific temporal trends across studies highlight the importance of prioritizing vulnerable groups in the design of pollution control policies.

Some of our findings are in part counter to our hypotheses and previous studies. While non-Hispanic Asian and Hispanic residents were found to be at greater relative risk of PM_{2.5} exposure on both circulatory and respiratory acute care hospitalizations than the white residents, with the highest increase over time among the non-Hispanic Asian residents, the relative risk of PM_{2.5} exposure on acute care utilization for non-Hispanic Black residents remained low and tended to decrease over time. There may be several reasons as to why we identified this trend, including lower health care access and utilization due to limited healthcare insurance coverage and low quality of care due to structural racism. Lack of healthcare coverage has been identified as one of the critical factors contributing to racial and ethnic differences in unmet medical needs, where non-Hispanic Black individuals were less likely to have access to health insurance in comparison to white individuals (Hargraves and Hadley, 2003). These lower rates of health insurance among non-Hispanic Black and Hispanic residents have caused barriers in healthcare access. Moreover, these residents are more likely to be provided with lower quality health care (Fiscella and Sanders, 2016). This could lead to an underestimation of the impact of PM_{2.5} exposure on adverse health outcomes in non-Hispanic Black residents in our analysis. Ultimately, more studies are needed to understand the racial and ethnic disparities in PM_{2.5} exposure impacts on adverse health outcomes and its underlying mechanism.

The rise in the association between PM_{2.5} exposure and both circulatory and respiratory acute care utilization highlights the need to reduce PM_{2.5} exposure for the total population living in California, with a prioritization of reducing this exposure for the subgroups who are experiencing greatest risk and widening disparities, such as the non-Hispanic Asian residents. Moreover, age should be considered for cause-specific health outcomes, as older adults were more susceptible to PM_{2.5} exposure impacts on circulatory acute care utilization, while younger individuals were more at risk for respiratory acute care utilization. While further research is needed to evaluate the most effective policies in reducing this PM_{2.5}-acute care utilization relationship, previous studies have highlighted the use of changing energy sources, phasing out specific substances or fuels, regulating chemical use, developing cleaning technologies, considering air pollution in land use decisions, reducing individual baseline risk of air pollution-related diseases, air quality communication and awareness, and shifting public attitude and behavior related to air pollution (Amann et al., 2020; Bell et al., 2011; Carnell et al., 2019; Jonidi Jafari et al., 2021; Kelly and Fussell, 2015; Ramírez et al., 2019; V. et al., 2011).

Limitations exist in this study. First, due to statistical power consideration, we restricted our analyses to 192 populous ZCTAs in California while rural areas were mostly excluded. Given the distribution of wildfires in California, rural areas in the northern mountains and Central Valley experienced the most wildfire smoke days (Do et al., 2024). In other words, our results might not be generalizable to such rural areas and should be evaluated by future studies. Second, unhoused individuals as well as unincorporated communities were not considered, as data are not readily available for these populations. This in part limits

the generalizability of these findings, as not everyone from the target Californian population was included in this study. Moreover, we did not consider intersectionality of the effect modification characteristics, although they are critical to study. It has been previously identified that intersections between race/ethnicity, sex/gender, socioeconomic status, and age, among other characteristics, should be examined collectively, as multiple marginalizations may lead to differential health outcomes that may not be identified from solely focusing on these characteristics independently (Bauer, 2014; Bowleg, 2012; Guan et al., 2021). We also did not examine the temporal changes in the relationship between exposure to specific sources of PM_{2.5} other than wildfire smoke and adverse health outcomes. We focused on wildfire-related PM_{2.5} due to the pressing consequences of wildfires in the state of California in recent years, particularly with the influence of climate change; however, investigating the consequences of additional PM_{2.5} sources should be further studied to identify specific strategies to reduce these exposures. Similarly, we focused on the time period of 2006 to 2019 and stratified this period to 2006 to 2012 and 2013 to 2019 to achieve equal statistical power in each stratum. Different time periods may also be explored if there is any plausible hypothesis that may explain this temporal trend (e.g. economic recession). This highlights the need for future studies to consider unhoused individuals, unincorporated communities, rural and less populated areas, other sources of PM_{2.5}, various time periods, and effect modifiers that reflect intersectionality.

This study also had several strengths. First, we included a considerable number of ZCTAs across California in this analysis. We also assessed the role of effect modification on the PM_{2.5}-acute care utilization relationship, including by sex, race/ethnicity, and age group in order to identify disparities in the impact of PM_{2.5} on these subpopulations. This is particularly useful for targeted interventions and policies focused on those who are most susceptible. Additionally, we considered several exposure lags ranging from single day lags to two days after the exposure as well as several approaches to assess the change in the PM_{2.5}-health relationship over time, from assuming no temporal trends, to comparing two periods, to assuming non-linear changes over time.

5. Conclusions

We examined whether temporal trends exist in the relationships between PM_{2.5} exposure and circulatory and respiratory acute care utilization in California from 2006 to 2019 and additionally investigated whether certain individuals are more susceptible to PM_{2.5} exposure than others, with regards to age, sex, and race/ethnicity. We identified a positive and increasing trend in both circulatory and respiratory acute care utilization risk with increasing PM_{2.5} exposure. We also observed effect modification of this relationship by age, sex, race/ethnicity, and extreme wildfire frequency. These findings emphasize the need to investigate this relationship in other populations and geographical regions, as this provides insight for policies and interventions aimed at reducing PM_{2.5} exposure.

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CRedit authorship contribution statement

Chen Chen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Anais Teyton:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Tarik Benmarhnia:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Chen Chen reports financial support was provided by National Institute on Aging. Tarik Benmarhnia reports financial support was provided by National Institute on Aging. Tarik Benmarhnia reports financial support was provided by Office of Environmental Health Hazard Assessment. Anis Teyton reports financial support was provided by Office of Environmental Health Hazard Assessment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to the code and data except for health data due to confidential considerations. I provided simulated health outcomes to facilitate replication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176543>.

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