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Key Points:

- $PM_{2.5}$ concentrations were estimated for 16 counties in Western North Carolina before, during, and after the 2016 wildfires in the region
- Emergency department respiratory and cardiovascular admissions showed a clear increase in odds with elevated wildfire smoke exposure
- Older adults and Black/African Americans were more vulnerable. Larger fires and more fires per county were associated with higher health burden at same day of exposure.

Supporting Information:

Supporting Information may be found in the online version of this article.

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Acute Health Effects of Wildfire Smoke Exposure During a Compound Event: A Case-Crossover Study of the 2016 Great Smoky Mountain Wildfires

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Abstract In 2016, unprecedented intense wildfires burned over 150,000 acres in the southern Appalachian Mountains in the United States. Smoke from these fires greatly impacted the region and exposure to this smoke was significant. A bidirectional case-crossover design was applied to assess the relationship between $PM_{2.5}$ (a surrogate for wildfire smoke) exposure and respiratory- and cardiovascular-related emergency department (ED) visits in Western North Carolina during these events. For 0-, 3-, and 7-day lags, findings indicated a significant increase in the odds of being admitted to the ED for a respiratory (ORs: 1.055, 95% CI: 1.048–1.063; 1.083, 1.074–1.092; 1.066, 1.058–1.074; respectively) or cardiovascular event (ORs: 1.052, 95% CI: 1.045–1.060; 1.074, 1.066–1.081; 1.067, 1.060–1.075; respectively) for every 5 $\mu g/m^3$ increase in $PM_{2.5}$ over a chosen cutpoint of 20.4 $\mu g/m^3$. For all endpoints assessed except for emphysema, there were statistically significant increases in odds from 5.1% to 8.3%. In general, this increase was most pronounced 3 days after exposure. Additionally, individuals aged 55+ generally experience higher odds of heart disease at the 3- and 7-day lag points, and Black/African Americans generally experience higher odds of asthma at the 3-day lag point. In general, larger fires and increased numbers of fires within counties resulted in higher health burden at same day exposure. In a secondary analysis, the odds of an ED visit increased by over 40% in several cases among people exposed to days above the Environmental Protection Agency 24-hr $PM_{2.5}$ standard of 35 $\mu g/m^3$. Our findings provide new understanding on the health impacts of wildfires on rural populations in the southeastern US.

Plain Language Summary The 2016 wildfires in the southern Appalachian Mountains in the United States burned over 150,000 acres. The smoke released by these fires resulted in concentrations of air pollutants well above federal regulations. Exposure to this smoke may result in more visits to the emergency room (ER) for respiratory and cardiovascular illnesses such as asthma and heart disease. To learn how this smoke impacted the health of people living and working in western North Carolina, we looked at data from ERs for these health issues and compared it with increases in air pollution from these wildfires. We found significant increases in odds of visiting the ER up to 7 days after exposure to this smoke. We found that people over 55 years old and Black/African Americans were more likely than other groups to visit the ER for these reasons. We also found counties with more and larger wildfires also led to worse higher odds of these illnesses in some cases. This is the first study exploring how these fires impact how many people go to the ER for respiratory and cardiovascular problems.

1. Introduction

From November to December in 2016, an intense drought resulted in unprecedented wildfires in the southeastern United States, particularly in the mountainous region of Southern Appalachia. These large-scale wildfires burned through dry forest and riparian zones, spreading quickly due to winds and high temperatures, in total burning over 150,000 acres (Andersen & Sugg, 2019; Chávez, 2016; James et al., 2020).

In addition to the direct impacts of the fires on the ground, the fires produced heavy smoke. Exposure to wildfire smoke has a positive association with general respiratory morbidity, including asthma exacerbation and chronic obstructive pulmonary disease (COPD) (Alman et al., 2016; Liu et al., 2017; Reid et al., 2016a). Wildfire smoke has also been linked to more instances of emergency room visits for asthma (Dohrenwend et al., 2013; Rappold et al., 2012), bronchitis (Delfino et al., 2009), and dyspnea (Dohrenwend et al., 2013; Schranz et al., 2010). For the

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effect of wildfire smoke exposure on cardiovascular morbidity, evidence is inconsistent with some studies finding negative or insignificant effects across all cardiovascular outcomes (Martin et al., 2013; Rappold et al., 2011) and others highlighting significant increases for specific outcomes like congestive heart failure (Delfino et al., 2009; Rappold et al., 2011), hypertension (Arbex et al., 2007) and ischemic heart disease (Johnston et al., 2014). Lag effects of acute exposures to wildfire smoke have also been studied. Between 0 and 7 days, wildfire smoke exposure has been significantly associated with respiratory and cardiovascular health outcomes (Chen et al., 2021; Hutchinson et al., 2018; Stowell et al., 2019).

The chemical and physical makeup of wildfire smoke and the negative health effects that individual components can cause have been well studied. Wildfire smoke is a heterogeneous mixture of many gaseous species such as volatile organic compounds, and particulate species including semi-volatile polycyclic aromatic hydrocarbons (Black et al., 2017). Particulate matter is the most visible component of wildfire smoke giving it its brown/gray hue. Exposure to particulate matter, particularly fine particulate matter, also called $PM_{2.5}$ (particulate matter with an aerodynamic diameter of 2.5 μm or less) has been linked to various health impacts, including the exacerbation of cardiovascular and respiratory conditions (Cascio, 2018; Kim et al., 2015).

Because of its known impact on health and welfare, $PM_{2.5}$ concentrations are regulated by the U.S. Environmental Protection Agency (EPA). $PM_{2.5}$ is directly measured with ground-based equipment, indirectly measured using satellite imagery, and modeled using various modeling techniques (Diao et al., 2019). In several studies, exposure to $PM_{2.5}$ has been used as a surrogate for exposure to wildfire smoke (e.g., Alman et al., 2016; Doubleday et al., 2020; Gan et al., 2017). However, there is not a standard concentration of $PM_{2.5}$ that indicates "exposed" versus "unexposed" populations. Alman et al. (2016) explored 24-hr $PM_{2.5}$ exposure as both a continuous variable and as a categorical variable at 10 μg/m^3 increments. Doubleday et al. (2020) used a primary set-point of 20.4 μg/m^3 which is the cutoff point between the "Moderate" and "Unhealthy for Sensitive Groups" categories as determined by the State of Washington. Finally, Gan et al. (2017) utilized a $PM_{2.5}$ concentration of 10 μg/m^3 or above as an indicator of smoke exposure. The 24-hr health-based $PM_{2.5}$ standard set by the EPA is 35 μg/m^3 (US Environmental Protection Agency, 2023), but has yet to be explored as a set point here in which above 35 μg/m^3 is considered a wildfire smoke exposure day and below is not. Regardless of the lack of an agreed upon exposure metric for wildfire smoke exposure, $PM_{2.5}$ still provides a valid metric for studying the epidemiological link between wildfire smoke exposure and health.

While the relationship between health and wildfire smoke exposure has been explored especially in the Western United States, research of this type for the Eastern United States is understudied. Limited examples include a recent study by Johnson and Garcia-Menendez (2022), which investigated multiple $PM_{2.5}$ estimates of mortality, work-loss days, ED visits from asthma, and hospital admissions for older adults during this same event. Yet, to our knowledge, no other analysis of the health effects from the 2016 Great Smoky Mountain wildfires exists.

The objective of this study is to examine the association between acute exposure to $PM_{2.5}$ and cardio-respiratory emergency department (ED) admissions in Western North Carolina (WNC) during the southeastern 2016 wildfire events using a case-crossover epidemiological study method. We explored the effect modification by age, gender, race and ethnicity, and insurance payor. Our results will shed light on an additional vulnerability for rural communities to wildfire health impacts.

2. Methods

2.1. Study Area and Population

The area of focus for this study was the 16 western-most counties in WNC as characterized by the WNC Health Network (see Figure 1) (WNC Health Network, N.D.). This area is quite mountainous and encompasses several national and state forests and parks. The population in this region in 2016 was approximately 1,578,288 (North Carolina Office of State Budget and Management, 2022) with the majority considered rural (North Carolina Office of State Budget and Management, 2018). Approximately 90% of the population was white, 4% Black or African American, 1% American Indian (AI)/Alaska Native, 1% Asian, and 2% "Other" (U.S. Census Bureau, 2016). The median income per county in the study area ranged from $41,977 to $59,928 based on data from 2017 to 2021 (U.S. Census Bureau, 2022). The region is characterized by a population with significant health disparities, including a higher proportion of cardio-respiratory comorbidity, complicated by poverty (Mountain Area Health Education Center, N.D.).

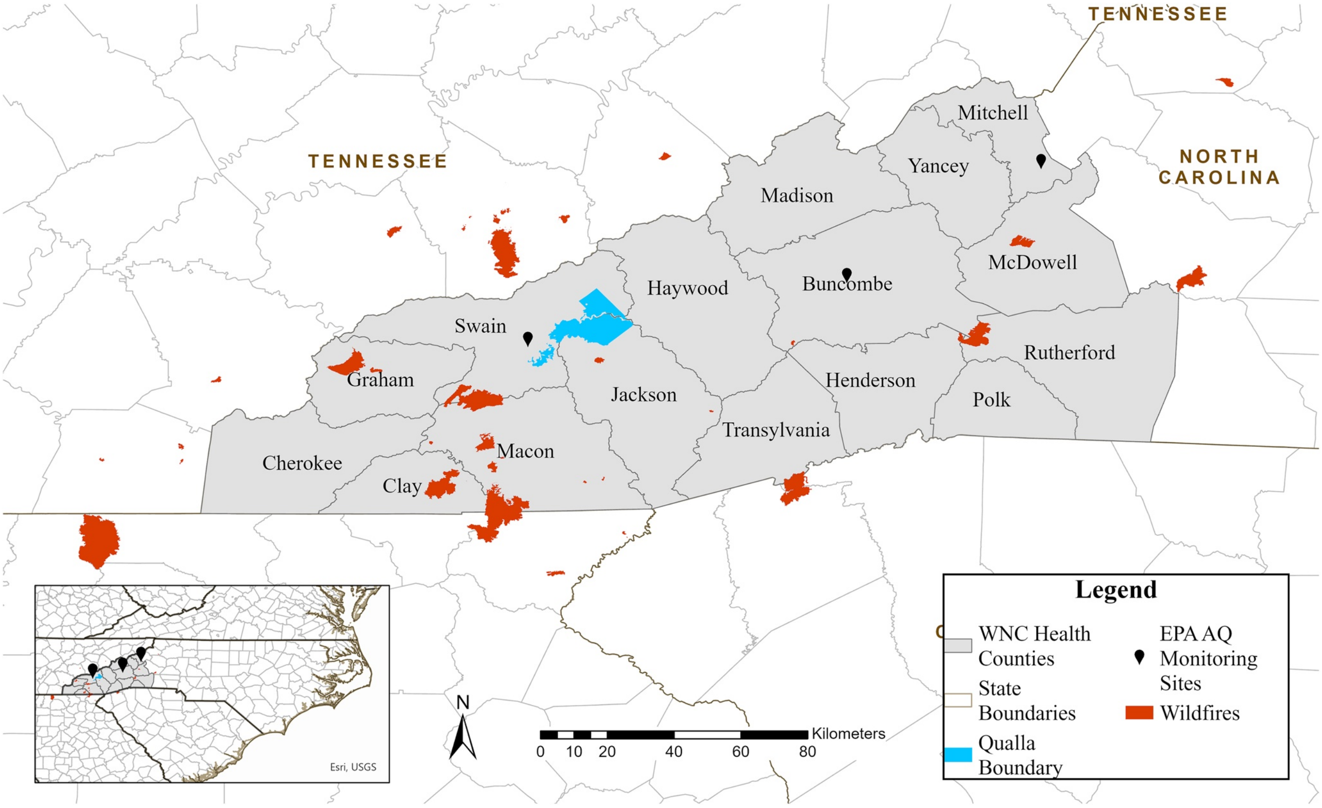

Figure 1. A map of the 16 counties in the study area (in gray). The Qualla Boundary in blue is the federally recognized territory of the Eastern Band of Cherokee Indians. Red represents wildfires over 100 acres and within 50 km of the study area during the study period. The black points represent the three Environmental Protection Agency monitoring sites in the study area.

2.2. Wildfire Events and $PM_{2.5}$ Concentration Estimates

Federal designated areas of disaster from the fires were recognized for the 7,000 acre North Carolina Party Rock Fire (11 November 2016 to 29 November 2016; FM-5161-NC) in Buncombe, Henderson, and Rutherford counties and the 6,000 acer North Carolina Chestnut Knob Fire (19 November 2016 to 4 December 2016; FM-5164-NC) in Burke County. In addition, other wildfires occurred in the region, including large fires like the 14,000 acre Tellico Fire in Swain County, NC and the 11,000 acer Chimney Top Fire in nearby east Tennessee. These fires resulted in substantial loss of property, life, and habitat and many in the region were exposed to high concentrations of wildfire smoke.

Due to the lack of real measurements (only three operational Federal Reference Monitors present in the study area) and the high spatial heterogeneity of air pollutant concentrations in this mountainous area, daily ambient $PM_{2.5}$ model estimates were obtained from the EPA's Fused Air Quality Surfaces Using Downscaling Tool for the 16 counties of interest. Data in μg/m^3 was averaged over the county areas at 24-hr intervals (12:00 a.m.–11:59 p.m.) between 01 October and 31 December 2016. $PM_{2.5}$ concentrations during the study period for each county are shown in Figure 2.

2.3. Patient Sample and Cardio-Respiratory Health Outcomes

For these counties studied, de-identified individual admissions to the ED were obtained from the University of North Carolina's Cecil G. Sheps Center for Health Services Research for all residents in the region. Data in ED records included patient demographics (e.g., age, race, ethnicity), insurance payor, residential zip code and county, admission and discharge date, and 25 potential diagnoses attributable to the ED visit.

Patients admitted to the ED for a respiratory or cardiovascular illness, between 01 November 2016 and 30 November 2016 in the WNC region, were considered a case and included in the analysis. The study sample was

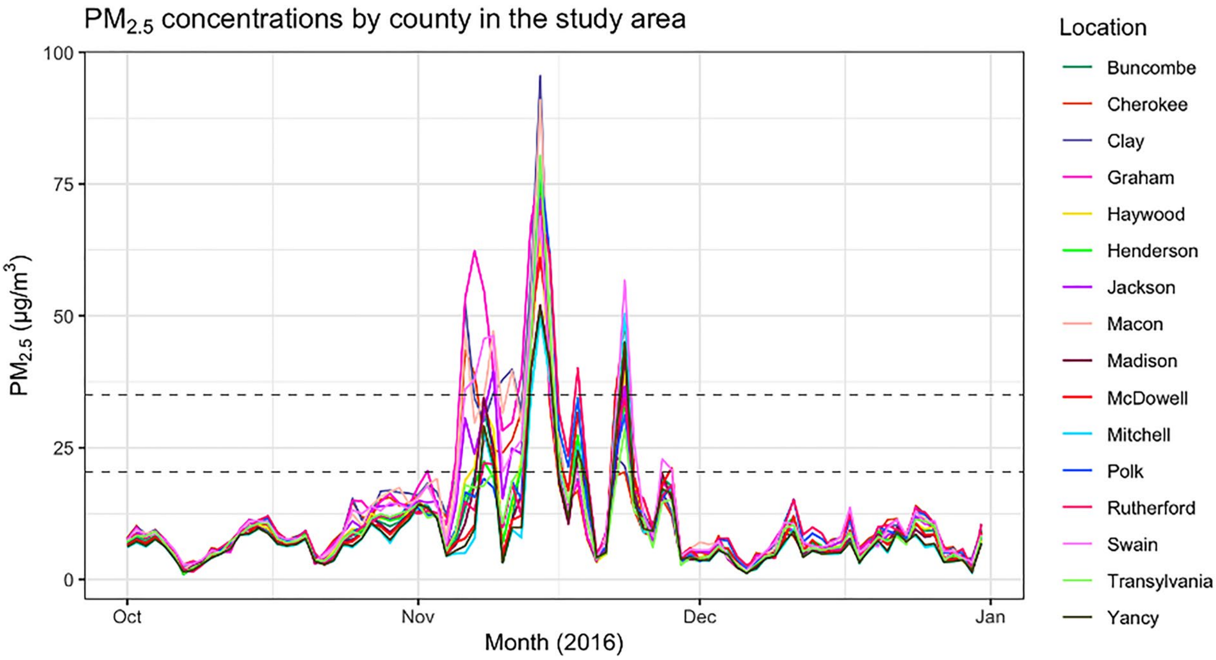

Figure 2. A time-series of 24-hr $PM_{2.5}$ concentration data in each county in the study area from 01 October to 31 December 2016. The bottom dashed line represents a $PM_{2.5}$ concentration of 20.4 µg/m^3 used as the primary cutpoint in this study. The top dashed line represents a $PM_{2.5}$ concentration of 35 µg/m^3 representing the Environmental Protection Agency's 24-hr standard.

further limited to individuals who were discharged within 2 days, calculated as the difference between admission and discharge dates, to include only residents who visited the ED and were not admitted inpatient. Using the World Health Organization online application for ICD 10 (International Classification of Diseases, Tenth Revision) codes, patients admitted for a respiratory (ICD-CM-10: J00-J99) and/or cardiovascular (ICD-CM-10: I10-I52) illness were first identified. Specific respiratory and cardiovascular conditions were then identified. These included asthma (ICD-CM-10: J45), COPD (ICD-CM-10: J44), emphysema (ICD-CM-10: J43), bronchitis (ICD-CM-10:J20.9, J40-J41), hypertension (ICD-CM-10: I10-I15.9), and heart disease (ICD-CM-10: I20-I52). All 25 possible diagnoses were included in patient flags for individual outcomes. An individual could be flagged for multiple outcomes.

2.4. Covariates

Patient demographics, including admission date, age group (≤18 years, 19–54, and 55+), sex (Female and Male), race (White, Black/African American, American Indian, and Asian/Native Hawaiian/Pacific Islander), ethnicity (Hispanic, non-Hispanic, and Unknown), and insurance payer (Commercial, Medicare, Medicaid, Uninsured, Other Government, and Other) were obtained for each ED visit and were used to differentiate impacts across these demographic characteristics.

2.5. Study Design

A symmetric, bidirectional case-crossover design was used to examine the acute health effects of exposure to poor air quality in the region during the 2016 wildfire events. In a bidirectional case-crossover study, each case is compared to their own artificial reference period(s) to control for long-term trends, seasonality, and individual characteristics (Carracedo-Martínez et al., 2010). For each case, there are four reference periods: 7 and 14 days before ($t-7$ and $t-14$) and after ($t+7$ and $t+14$) the ED admission.

2.6. Case and Control $PM_{2.5}$ Exposure From Wildfire Smoke

After cases were identified, ambient $PM_{2.5}$ was used as a surrogate for exposure to wildfire smoke (Karanasiou et al., 2021). Same-day smoke exposure (lag 0 or "same day exposure") was examined by appending 24-hr average $PM_{2.5}$ (in μg/m^3) to each observation by county and by either the date of admission (case period) or pre/post referent exposure dates (control periods). In this analysis, 3-day (lag 3) and 7-day (lag 7) effects of smoke exposure were also determined, representing the average exposure to $PM_{2.5}$ 3 and 7 days prior to an ED admission.

For the primary analysis, in accordance with Doubleday et al. (2020) a 20.4 μg/m^3 cutpoint was used to assess wildfire smoke exposure days. To further characterize wildfire smoke exposure, the number and size of the wildfires that occurred in each county were determined using the spatial extent of the wildfires and were appended to each case and control period. The number of wildfires was categorized into 0, 1, 2–3, and 4+ fires. The total square kilometers burned by wildfires were summed for each county and defined as small (0.01–1.0 km^2 burned), medium (1.01–30 km^2), and large (>30 km^2), based on previous research (Analitis et al., 2012). Analysis was completed in ArcGIS Pro 3.1 using simple area, distance and spatial selection methods (ESRI, 2021. ArcGIS Pro: Release 3.1. Redlands, CA: Environmental Systems Research Institute).

For a secondary analysis, a 35 μg/m^3 cutpoint was used to compare with the EPA 24-hr $PM_{2.5}$ primary standard.

2.7. Statistical Analysis

Descriptive statistics on demographic characteristics, wildfire smoke exposure, and health outcome frequencies and averages were determined.

A case-crossover data set with a case-control indicator (case vs. control period) and ambient $PM_{2.5}$ concentration exposure was created separately for each health outcome of interest. With each case-crossover data set, conditional logistic regression was used to determine the odds of a respective hospital admission per a five-unit increase in $PM_{2.5}$ (in μg/m^3) exposure by comparing case days with control days. Daily average temperature and rainfall data were included as potential time varying confounders in the analysis. The association between wildfire smoke exposure and health outcomes was examined at the 0-, 3-, and 7-day lag points in the separate models.

The effect of increasing $PM_{2.5}$ on the odds of all respiratory and cardiovascular outcomes was further analyzed by examining effect modification by: patient age in years, race, payer source, fire size, and number of wildfires in each county using an interaction term in the model. Results are reported as relative odds between cases and controls as odds ratios (ORs) with 95% confidence intervals.

3. Results

The sample consisted of 12,483 cases of either respiratory (n = 6,880) or cardiovascular (n = 8,246) illness. Demographic characteristics of cases are shown in Table 1. A large portion of cases (55%) were admitted to the ED with a respiratory illness. The most prevalent conditions were COPD (14% of all cases) and asthma (13%). Nearly 7% of cases had bronchitis and less than 1% had emphysema. Sixty-six percent (66%) of cases visited the ED with a cardiovascular illness. Hypertension (60%) and heart disease (22%) were common among the sample. A large portion of the sample used Medicare, Medicaid, or some other government plan as their primary health insurance (62%). The majority of cardiovascular outcomes (65%) occurred in older adults (55+ years) and white patients (92%); while respiratory illnesses occurred in children (22%), adults (42%), and older adults (37%) without a clear majority (Table 1).

The mean 0-, 3-, and 7-day-lag exposures to $PM_{2.5}$ in cases were 19.77, 20.40, and 20.14 μg/m^3, respectively compared to controls, with mean 0-, 3-, and 7-day exposures to $PM_{2.5}$ of 16.74, 16.43, and 16.60 μg/m^3, respectively. Roughly 16% of cases experienced at least one above-35 μg/m^3 day at each lag point (data not shown). Seventy-two percent (72%) of cases directly experienced a wildfire within their county during the study period. More than 60% of cases lived in a county that experienced a medium-sized wildfire; 36% were exposed to one fire; 22% were exposed to two or three; and 15% were exposed to four or more fires.

3.1. Overall Wildfire Smoke-Health Effects

Except for emphysema, there was a significant positive association between a 5-unit increase in $PM_{2.5}$ (in μg/m^3) exposure at the 0- and 3-day lag points, and the increased likelihood of a respective ED visit with each cardio and respiratory outcome (Figure 3). While results across lag points were only marginally different across cardiovascular or respiratory outcomes, the 3-day associations for all respiratory (except emphysema at the 7-day lag) and all cardiovascular outcomes were the strongest associations observed.

Table 1
Respiratory and Cardiovascular Outcomes by Demographic

	Diagnosis															
Characteristic	All respiratory		Asthma		COPD		Emphysema		Bronchitis		All cardiovascular		Hypertension		Heart disease	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Age																
0–18 years	1,492	21.69	301	18.52	0	0.00	0	0.00	117	14.03	40	0.49	31	0.42	11	0.39
19–54 years	2,861	41.58	855	56.62	455	25.99	19	25.33	466	55.88	2,826	34.27	2,594	34.86	529	18.93
55+ years	2,527	36.73	469	28.86	1,296	74.01	56	74.67	251	30.10	5,380	65.24	4,817	64.73	2,254	80.67
Sex																
Female	4,105	59.67	1,081	66.52	1,031	58.88	34	45.33	514	61.63	4,635	56.21	4,228	56.81	1,425	51.00
Male	2,775	40.33	544	33.48	720	41.12	41	54.67	320	38.37	3,610	43.78	3,213	43.17	1,369	49.00
Unknown	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.01	1	0.01	0	0.00
Race																
White	6,122	90.98	1,380	86.14	1,628	93.78	72	96.00	754	92.29	7,483	91.88	6,731	91.49	2,582	93.65
Black/African American	533	7.92	203	12.67	96	5.53	2	2.67	57	6.98	597	7.33	566	7.69	157	5.69
American Indian	54	0.80	12	0.75	6	0.35	0	0.00	5	0.61	45	0.55	44	0.60	9	0.33
Asian, native Hawaiian, or Pacific Islander	20	0.30	7	0.44	6	0.35	1	1.33	1	0.12	19	0.23	16	0.22	9	0.33
Ethnicity																
Non-Hispanic	6,463	93.94	1,522	93.66	1,724	98.46	73	97.33	803	96.28	8,038	97.48	7,261	97.57	2,722	97.42
Hispanic	190	2.76	42	2.58	10	0.57	0	0.00	16	1.92	99	1.20	89	1.20	34	1.22
Unknown	227	3.30	61	3.75	17	0.97	2	2.67	15	1.80	109	1.32	92	1.24	38	1.36
Payer																
COMM/HMO	1,767	25.68	371	22.83	360	20.56	23	30.67	244	29.26	2,341	28.39	2,128	28.59	720	25.77
Medicaid	2,371	34.46	623	38.34	292	16.68	9	12.00	246	29.50	1,224	14.84	1,107	14.88	300	10.74
Medicare	1,853	26.93	418	25.72	966	55.17	38	50.67	171	20.50	3,811	46.22	3,415	45.89	1,608	57.55
Other gov	80	1.16	12	0.74	32	1.83	0	0.00	8	0.96	144	1.75	133	1.79	38	1.36
Other	18	0.26	7	0.43	2	0.11	1	1.33	2	0.24	42	0.51	34	0.46	14	0.50
Uninsured	791	11.50	194	11.94	99	5.65	4	5.33	163	19.54	684	8.29	625	8.40	114	4.08

Note. Footnote: COPD = chronic obstructive pulmonary disease and COMM/HMO = Community/Health Maintenance Organization.

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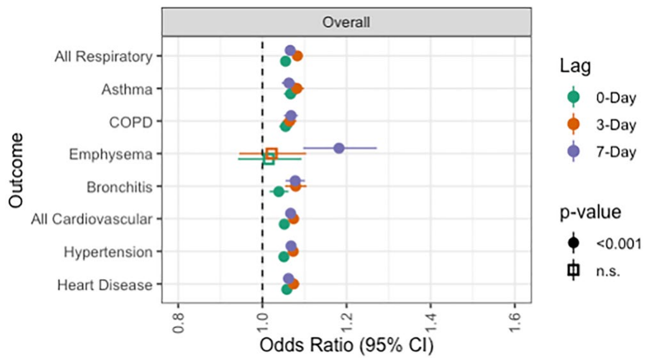

Figure 3. Forest plot of odds ratios of outcomes by overall sample. n.s. = not significant.

3.2. Age Differences in Wildfire Smoke-Related Health Risks

We observed important differences across age groups (Figure 4a); whereby all age groups were likely to present with an increase odds in overall acute respiratory conditions, children (≤18 years) were more likely to present with an asthma-related ED visit, and adults (age 19–54 years) and older adults (55+ years) were more likely to present to the ED with acute symptoms related to asthma, COPD, and bronchitis across the three lag periods. Finally, the odds of an acute cardiovascular event during the wildfire events were generally similar for adult and older adult populations, with the exception of a higher odds for older adults at the 7-day lag (OR: 1.073, 95% CI: 1.064, 1.083).

3.3. Racial Differences in Wildfire Smoke-Related Health Risks

In general, the likelihood of a respiratory-related ED visit was higher among African Americans compared to all other racial groups, particularly for an

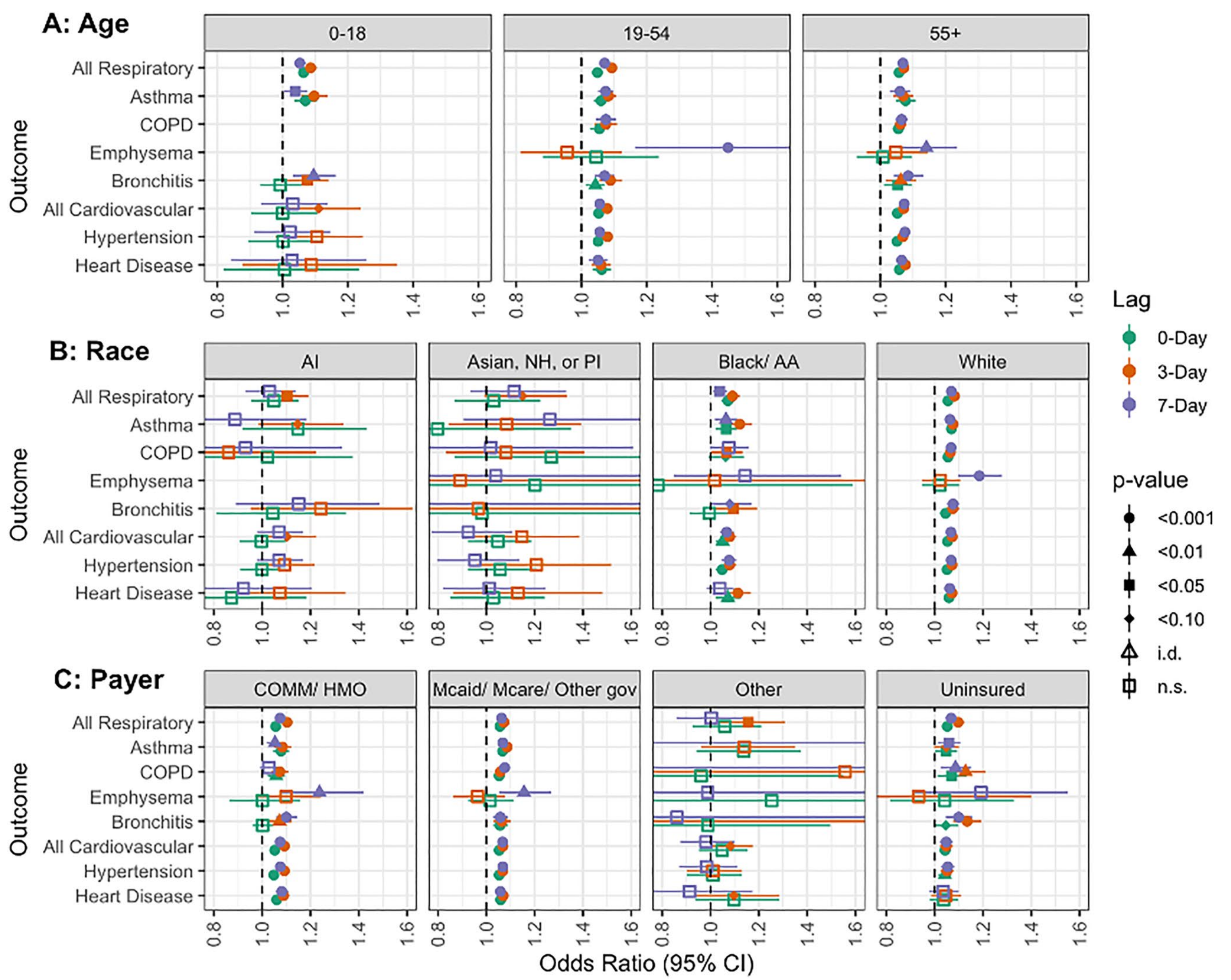

Figure 4. Forest plots of odds ratios of outcomes by covariate classes for age range (in years, (a)), racial demographics (AI = American Indian, NH = Native Hawaiian, PI = Pacific Islander, AA = African American, (b)), and payer (COMM/HMO = Commercial/Health Maintenance Organization, MCaid/Mcare/Other gov = Medicaid, Medicare, Other government, (c)). i.d. = insufficient data and n.s. = not significant.

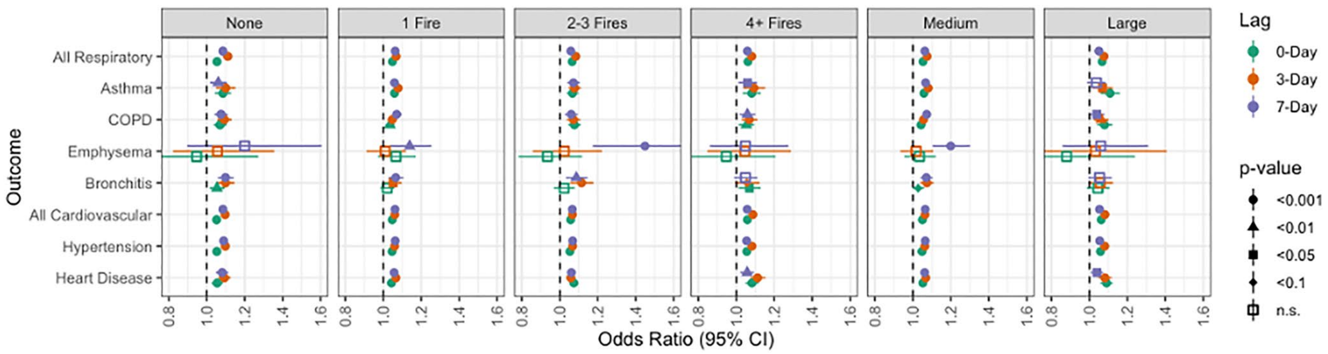

Figure 5. Forest plots of odds ratios of outcomes by fire count per county and fire size (large = greater than 30 km^2 and medium = less than 30 km^2). n.s. = not significant.

asthma admission on the same day (OR: 1.065, 95% CI: 1.021–1.110) or 3 days after exposure (OR: 1.121, 95% CI: 1.072–1.172) to high concentrations of $PM_{2.5}$, respectively (Figure 4b). More pronounced disparities in cardio-respiratory ED admissions would be likely among AI and Asian, Native Hawaiian, or Pacific Islander, if we had a sufficient sample size of cases in the region.

3.4. Payer Source Differences in Wildfire Smoke-Related Health Risks

We did not observe a higher odds of cardiac or respiratory-related ED admissions in Medicaid/Medicare beneficiaries or for medically uninsured populations following exposure to $PM_{2.5}$ (Figure 4c).

3.5. Wildfire Classification

In general, there were higher odds for all respiratory and cardiovascular events in counties with large wildfires at the 0-day lag point (OR = 1.067, 95% CI: 1.046–1.088, and OR = 1.062, 95% CI: 1.044–1.080, respectively), but not at the 3- and 7-day lag points. This trend was similar when comparing the number of fires per county (0, 1, 2–3, or 4+). See Figure 5.

3.6. EPA Standard Cutpoint Classification

A sensitivity analysis comparing the odds of an ED visit (case vs. control) between days with $PM_{2.5}$ above 35 μg/m^3 and below 35 μg/m^3 at the 0-, 3-, and 7-day lag points was conducted. Medians of 14.1%, 14.0%, and 13.0% of cases experienced a day in which exposures were above 35 μg/m^3 for the 0-, 3-, and 7-day lag points, respectively.

Overall, ORs were substantially higher than 5 μg/m^3 unit increases at the 20.4 μg/m^3 cutpoint and similar to the primary analysis. For any respiratory illness, ORs were generally higher at the 3-day, then 7-day, then 0-day lag points (OR = 1.390 95% CI: 1.290–1.49, OR = 1.380 95% CI: 1.281–1.486, and OR = 1.191 95% CI: 1.106–1.283, respectively). Particularly, the odds of being admitted for emphysema were almost 300% higher at the 7-day lag point (OR = 2.93, 95% CI: 1.59, 5.41). However, these results should be interpreted with caution since there were only 75 total reported cases during the study period. For cardiovascular outcomes, ORs followed the same trend as respiratory outcomes, but were more pronounced for the 0- and 7-day lag points (OR = 1.207 95% CI: 1.128–1.293, and OR = 1.409 95% CI: 1.315–1.509, respectively). Odds ratios for hypertension increased over the 0- to 7-day lag period from 1.192 (95% CI: 1.109–1.281) to 1.412 (95% CI: 1.314, 1.519), respectively. See Figure S1 in Supporting Information S1.

Complete tables of all ORs are provided in the Supporting Information S1.

4. Discussion

In this study, acute same-day and lagged 3- and 7-day exposure to elevated wildfire smoke during the unprecedented 2016 wildfire season in WNC was associated with an increase in cardiac and respiratory disease burden.

Children (≤18 years) were more likely to be admitted for asthma-related visits, while adults in the region were much more likely to experience an ED visit for an aggravated cardiovascular or respiratory episode. Population sensitivity also varied across racial groups; whereby African American residents were much more likely to experience an acute asthma event. The number of wildfires present within a county appeared to be a better wildfire smoke exposure indicator compared to the size of the wildfire events. The associations between respiratory outcomes and $PM_{2.5}$ exposure from wildfire smoke were consistent with previous studies that focus on the Western US (Alman et al., 2016; Doubleday et al., 2020).

Our results indicate that exposures to wildfire smoke during the 2016 wildfire season in North Carolina were associated with an increased odds of any respiratory- or cardiovascular-related ED visit for same-day, 3-, and 7-day lagged effects. Prior studies that employed a case-crossover design and that examined population-based exposure to wildfire smoke in the southeastern U.S. found similar effects (Alman et al., 2016; Gan et al., 2017; Rappold et al., 2012). Hutchinson et al. (2018) also used a case-crossover design and found much stronger associations between asthma and respiratory ED admissions (Hutchinson et al., 2018). Interestingly, our results were indicative of a lagged effect, while others generally found the strongest effects from same-day exposures (Alman et al., 2016; Gan et al., 2017).

Children exposed to wildfire smoke in this analysis were more likely to present with an overall respiratory- or specifically asthma- or bronchitis-related ED admissions. A systematic review by Henry et al. (2021) compiled evidence suggesting a "moderate certainty" of an association between wildfire smoke exposure and ED admissions for respiratory events among children. However, they did not find a significant linkage between wildfire smoke and pediatric asthma ED visits specifically (Henry et al., 2021). In contrast, in this study, the increase in odds for ED visits for asthma for cases aged 0–18 were significant especially for the 0- and 3-day lag points (7.1%, 95% CI: 3.7%–10.5%, and 9.8%, 95% CI: 5.9%–13.9%, respectively). Still, it is possible that the relationship among children with asthma is much harder to assess, and future studies should consider factors like time spent indoors, indoor asthma triggers, and medication usage which were not assessed here.

In addition to respiratory admissions, cardiovascular-related admissions were significantly greater among adults exposed to wildfire smoke. This association was similar between the 19–54 and 55+ age groups for the same day and 3-day lag points (for same-day: OR = 1.053 95% CI: 1.041, 1.066, and OR = 1.053 95% CI: 1.043, 1.061, respectively and for 3-day: OR = 1.079 95% CI: 1.066, 1.092, and OR = 1.071 95% CI: 1.062, 1.080, respectively). However, at the 7-day lag period, ORs for cardiovascular endpoints were substantially higher for the 55+ age group compared to the 19–54 age group (OR = 1.073 95% CI: 1.064, 1.083, and OR = 1.056 95% CI: 1.043, 1.069, respectively). However, the results across age groups were not significantly different as to suggest effect modification by age. Alman et al. (2016) found higher odds only among adults 65 and older and Magzamen et al. (2021) did not determine any difference by age.

Population sensitivity also varied across racial groups. African American residents exposed to wildfire smoke were significantly more likely to experience an acute asthma event, as were American Indian residents, though that association was not statistically significant. Few studies have examined how racial and ethnic differences in the association between wildfire smoke and ED admissions (Kondo et al., 2019), and none have examined this association in the southeastern US. One study used tertiles of race at the zip code level and did not find any significantly greater risk for zip codes with larger African American populations (Reid et al., 2016b). Liu et al. (2017) found significantly greater risk among African Americans exposed to wildfire smoke compared to white individuals; however, this analysis was partially constrained by sample size. More research is needed to determine if and how race as a social construct might affect the impact of between wildfire smoke on health outcomes.

While this study is the first of its kind to be conducted in the Eastern United States, several studies employing a case-crossover design have been published in the Mountain West. During the Colorado wildfire seasons from 2010 to 2015, Magzamen et al. (2021) also observed a statistically significant increase in odds for respiratory endpoints at the 3-day lagged period, but, unlike our study, no association was observed for any other lag-period. And, for all cardiovascular illness, they only identified a statistical increase at a 1-day lag, a lag period we did not analyze. During a 2007 San Diego County wildfire, Hutchinson et al. (2018) did not find any statistically significant increase in risk for both respiratory and cardiovascular admissions 1–5 days after exposure. Doubleday et al. (2020), who studied mortality rather than ED admissions, only found a statistically significant increase in odds for COPD for same day exposure. Compared to these and other published studies, the magnitude of increase in odds in our study appears to be broadly stronger.

Currently there is no consensus on a standard measure or indicator to characterize population-based exposure to wildfire smoke (Karanasiou et al., 2021). In this analysis, the number of wildfires within a county appeared to be a better exposure indicator than the size of the wildfire events. Proximity to the wildfires, unmeasured in this study, could be an important third variable (Matz et al., 2020), and a recent study provided support for using proximity to fires as a proxy for smoke exposure (Smith & Chi, 2023). To account for these and other factors, like weather and wind, researchers have traditionally used plume modeling to estimate the presence of harmful smoke from wildfires (Wilkins et al., 2022).

For the secondary analysis, when comparing across 35 $\mu g/m^3$ days, the effects were consistently stronger than those for the primary analysis. In addition, effects were strongest, for most outcomes, at the 3- and 7-day lagged exposures. To our knowledge, this study is the first to try the approach of using the EPA's 24-hr $PM_{2.5}$ standard as a wildfire-smoke exposure cutpoint. Using the EPA standard concentration results in substantially elevated ORs for almost all outcomes. These clear signals provide evidence for its ease of use as a binary cutpoint that can be easily compared to and supportive of federal regulations.

Whatever metric is used to determine exposure to wildfire smoke, it is clear that there were significant negative health implications for this exposed population. Fortunately, there are several manners in which exposure to wildfire smoke can be reduced. These include individual-level actions to reduce exposure to wildfire smoke during events such as leaving the affected area completely, staying indoors, using high efficiency particulate air filters, and using N95 respirators (Laumbach, 2019). However, personal behavior to mitigate exposure to wildfire smoke has been found to vary greatly (Burke et al., 2022). There is ample evidence that indoor $PM_{2.5}$ concentrations during wildfire smoke events are consistently lower than outdoor concentrations. For example, in a recent study using low cost sensors in the western United States, O'Dell et al. (2022) found indoor $PM_{2.5}$ concentrations to be 40%–71% lower than outdoor concentrations during wildfire events. However, during these events, indoor concentrations will still be elevated. A 2021 American Society of Heating, Refrigerating and Air-Conditioning Engineers column provides a framework for getting larger buildings that use air handling units such as commercial buildings, schools, and larger multi residential buildings wildfire season ready which includes developing a smoke readiness plan, testing heating, ventilation, and air conditioning (HVAC systems), upgrading filters, and maintaining positive air pressure in the building (Javins et al., 2021). However, many people in the study area, particularly those living in more rural areas live in single family homes, and those who are of lower socioeconomic status are likely to live in "leakier" homes, which allow more pollution from outdoor air to infiltrate in. Reducing exposures to wildfire smoke is vital to protect health as incidences of wildfires are only expected to increase in the southeastern United States due to climate change (Kupfer et al., 2020).

5. Strengths and Limitations

This study had several notable strengths. First, this work is one of the first to investigate the health effects of the widespread 2016 wildfire event in WNC, a region that traditionally does not experience large wildfire events. Western North Carolina is a location with significant rural health disparities, including elevated levels of cardiovascular and respiratory diseases (Dwyer-Lindgren et al., 2017; Mountain Area Health Education Center, N.D.; Roth et al., 2017). Second, we were able to examine the impacts of this wildfire event over a large 16-county region with multiple wildfire exposure metrics and lag periods, health outcomes, and vulnerable population subgroups considered.

Our findings have a few limitations. First, with all studies using ambient estimates of $PM_{2.5}$ exposure, whether ground- or satellite-based measurements or modeled concentrations, exposure mischaracterization of $PM_{2.5}$ concentrations is likely (Richmond-Bryant & Long, 2020). Further, the location of the smoke exposure was determined using residential location derived from the ED administrative data; although, most population-based health-wildfire studies use a county-level proxy for exposure (e.g., Magzamen et al., 2021; Reid et al., 2016a, 2016b).

Finally, case-crossover studies can effectively and efficiently assess associations between ephemeral exposures and subsequent outcomes while controlling for temporal, spatial, and demographic factors (Wang et al., 2011). However, the bidirectional case-crossover design does not account for the potential for overlap bias, which is generally small (Janes et al., 2005). Finally, this study did not study health outcomes outside of respiratory and cardiovascular outcomes; however, prior studies have shown an increase in wildfire and mental maternal health outcomes (Eisenman & Galway, 2022; Evans et al., 2022).

6. Conclusions

Our study adds to a limited evidence base examining wildfire impacts in rural and medically underserved populations. Results showed acute and lagged exposure to wildfire smoke resulted in increased cardio-respiratory disease burden in adult and child populations. More research is needed to understand population vulnerability factors during large-scale fire events in understudied rural and medically vulnerable regions in the southeastern US. Future studies can seek to identify enhanced wildfire exposure assessment metrics to better understand health risks.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

$PM_{2.5}$ and wildfire data as well as R code to produce plots are published at Zenodo data repository. Data is available at Duncan et al. (2023). The Protected Health Information data as provided by the University of North Carolina's Cecil G. Sheps Center for Health Services Research is highly sensitive and cannot be shared in accordance with the researchers' data use agreement.

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References

Alman, B. L., Pfister, G., Hao, H., Stowell, J., Hu, X., Liu, Y., & Strickland, M. J. (2016). The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: A case crossover study. *Environmental Health*, *15*(1), 64. https://doi.org/10.1186/s12940-016-0146-8

Analitis, A., Georgiadis, I., & Katsouyanni, K. (2012). Forest fires are associated with elevated mortality in a dense urban setting. *Occupational and Environmental Medicine*, *69*(3), 158–162. https://doi.org/10.1136/oem.2010.064238

Andersen, L. M., & Sugg, M. M. (2019). Geographic multi-criteria evaluation and validation: A case study of wildfire vulnerability in western North Carolina, USA following the 2016 wildfires. *International Journal of Disaster Risk Reduction*, *39*, 101123. https://doi.org/10.1016/j.ijdrr.2019.101123

Arbex, M. A., Martins, L. C., de Oliveira, R. C., Pereira, L. A. A., Arbex, F. F., Cançado, J. E. D., et al. (2007). Air pollution from biomass burning and asthma hospital admissions in a sugar cane plantation area in Brazil. *Journal of Epidemiology & Community Health*, *61*(5), 395–400. https://doi.org/10.1136/jech.2005.044743

Black, C., Tesfaigzi, Y., Bassein, J. A., & Miller, L. A. (2017). Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. *Environmental Toxicology and Pharmacology*, *55*, 186–195. https://doi.org/10.1016/j.etap.2017.08.022

Burke, M., Heft-Neal, S., Li, J., Driscoll, A., Baylis, P., Stigler, M., et al. (2022). Exposures and behavioural responses to wildfire smoke. *Nature Human Behaviour*, *6*(10), 10–1361. https://doi.org/10.1038/s41562-022-01396-6

Carracedo-Martínez, E., Taracido, M., Tobias, A., Saez, M., & Figueiras, A. (2010). Case-crossover analysis of air pollution health effects: A systematic review of methodology and application. *Environmental Health Perspectives*, *118*(8), 1173–1182. https://doi.org/10.1289/ehp.0901485

Cascio, W. E. (2018). Wildland fire smoke and human health. *Science of the Total Environment*, *624*, 586–595. https://doi.org/10.1016/j.scitotenv.2017.12.086

Chávez, K. (2016). *Outbreak of WNC wildfires takes toll on wildlife, environment*. The Asheville Citizen Times. Retrieved from https://www.citizen-times.com/story/news/local/2016/11/18/outbreak-wnc-wildfires-takes-toll-wildlife-environment/93788956/

Chen, G., Guo, Y., Yue, X., Tong, S., Gasparrini, A., Bell, M. L., et al. (2021). Mortality risk attributable to wildfire-related $PM_{2.5}$ pollution: A global time series study in 749 locations. *The Lancet Planetary Health*, *5*(9), e579–e587. https://doi.org/10.1016/S2542-5196(21)00200-X

Delfino, R. J., Brummel, S., Wu, J., Stern, H., Ostro, B., Lipsett, M., et al. (2009). The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occupational and Environmental Medicine*, *66*(3), 189–197. https://doi.org/10.1136/oem.2008.041376

Diao, M., Holloway, T., Choi, S., O'Neill, S. M., Al-Hamdan, M. Z., Van Donkelaar, A., et al. (2019). Methods, availability, and applications of $PM_{2.5}$ exposure estimates derived from ground measurements, satellite, and atmospheric models. *Journal of the Air & Waste Management Association*, *69*(12), 1391–1414. https://doi.org/10.1080/10962247.2019.1668498

Dohrenwend, P. B., Le, M. V., Bush, J. A., & Thomas, C. F. (2013). The impact on emergency department visits for respiratory illness during the southern California wildfires. *Western Journal of Emergency Medicine*, *14*(2), 79–84. https://doi.org/10.5811/westjem.2012.10.6917

Doubleday, A., Schulte, J., Sheppard, L., Kadlec, M., Dhammapala, R., Fox, J., & Busch Isaksen, T. (2020). Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: A case-crossover study. *Environmental Health*, *19*(1), 4. https://doi.org/10.1186/s12940-020-0559-2

Duncan, S., Reed, C., Spurlock, T., Runkle, J., & Sugg, M. (2023). Datasets and R code associated with: Acute health effects of wildfire smoke exposure during a compound event: A case-crossover study of the 2016 Great Smoky Mountain wildfires [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.8403272

Dwyer-Lindgren, L., Bertozzi-Villa, A., Stubbs, R. W., Morozoff, C., Shirude, S., Naghavi, M., et al. (2017). Trends and patterns of differences in chronic respiratory disease mortality among US counties, 1980-2014. *JAMA*, *318*(12), 1136–1149. https://doi.org/10.1001/jama.2017.11747

Eisenman, D. P., & Galway, L. P. (2022). The mental health and well-being effects of wildfire smoke: A scoping review. *BMC Public Health*, *22*(1), 2274. https://doi.org/10.1186/s12889-022-14662-z

ESRI. (2021). *ArcGIS Pro (GIS software). Version 3.1*. Environmental Systems Research Institute, Inc.

Evans, J., Bansal, A., Schoenaker, D. A., Cherbuin, N., Peek, M. J., & Davis, D. L. (2022). Birth Outcomes, health, and health care needs of childbearing women following wildfire disasters: An integrative, state-of-the-science review. *Environmental Health Perspectives*, *130*(8), 086001. https://doi.org/10.1289/EHP10544

Gan, R. W., Ford, B., Lassman, W., Pfister, G., Vaidyanathan, A., Fischer, E., et al. (2017). Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions. *GeoHealth*, *1*(3), 122–136. https://doi.org/10.1002/2017GH000073

Henry, S., Ospina, M. B., Dennett, L., & Hicks, A. (2021). Assessing the risk of respiratory-related healthcare visits associated with wildfire smoke exposure in children 0–18 Years old: A systematic review. *International Journal of Environmental Research and Public Health*, *18*(16), 8799. https://doi.org/10.3390/ijerph18168799

Hutchinson, J. A., Vargo, J., Milet, M., French, N. H. F., Billmire, M., Johnson, J., & Hoshiko, S. (2018). The San Diego 2007 wildfires and Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: An observational study of smoke exposure periods and a bidirectional case-crossover analysis. *PLoS Medicine*, *15*(7), e1002601. https://doi.org/10.1371/journal.pmed.1002601

James, N. A., Abt, K. L., Frey, G. E., Han, X., & Prestemon, J. P. (2020). *Fire in the Southern Appalachians: Understanding impacts, interventions, and future fire events*. U.S. Department of Agriculture, Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-249

Janes, H., Sheppard, L., & Lumley, T. (2005). Case-crossover analyses of air pollution exposure data: Referent selection strategies and their implications for bias. *Epidemiology*, *16*(6), 717–726. https://doi.org/10.1097/01.ede.0000181315.18836.9d

Javins, T., Robarge, G., Gibb Snyder, E., Nilsson, G., & Emmerich, S. (2021). Protecting building occupants from smoke during wildfire and prescribed burn events. *ASHRAE Journal*. Retrieved from https://www.epa.gov/sites/default/files/2021-05/documents/ashrae_journal_article_march_2021-tagged.pdf

Johnson, M. M., & Garcia-Menendez, F. (2022). Uncertainty in health impact assessments of smoke from a wildfire event. *GeoHealth*, *6*(1), e2021GH000526. https://doi.org/10.1029/2021GH000526

Johnston, F. H., Purdie, S., Jalaludin, B., Martin, K. L., Henderson, S. B., & Morgan, G. G. (2014). Air pollution events from forest fires and emergency department attendances in Sydney, Australia 1996–2007: A case-crossover analysis. *Environmental Health*, *13*(1), 105. https://doi.org/10.1186/1476-069X-13-105

Karanasiou, A., Alastuey, A., Amato, F., Renzi, M., Stafoggia, M., Tobias, A., et al. (2021). Short-term health effects from outdoor exposure to biomass burning emissions: A review. *Science of the Total Environment*, *781*, 146739. https://doi.org/10.1016/j.scitotenv.2021.146739

Kim, K.-H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment International*, *74*, 136–143. https://doi.org/10.1016/j.envint.2014.10.005

Kondo, M. C., De Roos, A. J., White, L. S., Heilman, W. E., Mockrin, M. H., Gross-Davis, C. A., & Burstyn, I. (2019). Meta-analysis of heterogeneity in the effects of wildfire smoke exposure on respiratory health in North America. *International Journal of Environmental Research and Public Health*, *16*(6), 960. https://doi.org/10.3390/ijerph16060960

Kupfer, J. A., Terando, A. J., Gao, P., Teske, C., & Hiers, J. K. (2020). Climate change projected to reduce prescribed burning opportunities in the south-eastern United States. *International Journal of Wildland Fire*, *29*(9), 764–778. https://doi.org/10.1071/WF19198

Laumbach, R. J. (2019). Clearing the air on personal interventions to reduce exposure to wildfire smoke. *Annals of the American Thoracic Society*, *16*(7), 815–818. https://doi.org/10.1513/AnnalsATS.201812-894PS

Liu, J. C., Wilson, A., Mickley, L. J., Ebisu, K., Sulprizio, M. P., Wang, Y., et al. (2017). Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *American Journal of Epidemiology*, *186*(6), 730–735. https://doi.org/10.1093/aje/kwx141

Magzamen, S., Gan, R. W., Liu, J., O'Dell, K., Ford, B., Berg, K., et al. (2021). Differential cardiopulmonary health impacts of local and long-range transport of wildfire smoke. *GeoHealth*, *5*(3), e2020GH000330. https://doi.org/10.1029/2020GH000330

Martin, K. L., Hanigan, I. C., Morgan, G. G., Henderson, S. B., & Johnston, F. H. (2013). Air pollution from bushfires and their association with hospital admissions in Sydney, Newcastle and Wollongong, Australia 1994–2007. *Australian & New Zealand Journal of Public Health*, *37*(3), 238–243. https://doi.org/10.1111/1753-6405.12065

Matz, C. J., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., et al. (2020). Health impact analysis of $PM_{2.5}$ from wildfire smoke in Canada (2013–2015, 2017–2018). *Science of the Total Environment*, *725*, 138506. https://doi.org/10.1016/j.scitotenv.2020.138506

Mountain Area Health Education Center. (N.D.). Rural health disparities in WNC. Retrieved from https://mahec.net/rhi/wnc-health-disparities

North Carolina Office of State Budget and Management. (2018). The urban and rural faces of North Carolina. Retrieved from https://files.nc.gov/ncosbm/documents/files/2018ACSNC.pdf

North Carolina Office of State Budget and Management. (2022). County/state population projections. Retrieved from https://www.osbm.nc.gov/facts-figures/population-demographics/state-demographer/countystate-population-projections#ProjectionData

O'Dell, K., Ford, B., Burkhardt, J., Magzamen, S., Anenberg, S. C., Bayham, J., et al. (2022). Outside in: The relationship between indoor and outdoor particulate air quality during wildfire smoke events in western US cities. *Environmental Research: Health*, *1*(1), 015003. https://doi.org/10.1088/2752-5309/ac7d69

Rappold, A. G., Cascio, W. E., Kilaru, V. J., Stone, S. L., Neas, L. M., Devlin, R. B., & Diaz-Sanchez, D. (2012). Cardio-respiratory outcomes associated with exposure to wildfire smoke are modified by measures of community health. *Environmental Health*, *11*(1), 71. https://doi.org/10.1186/1476-069X-11-71

Rappold, A. G., Stone, S. L., Cascio, W. E., Neas, L. M., Kilaru, V. J., Carraway, M. S., et al. (2011). Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. *Environmental Health Perspectives*, *119*(10), 1415–1420. https://doi.org/10.1289/ehp.1003206

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016a). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, *124*(9), 1334–1343. https://doi.org/10.1289/ehp.1409277

Reid, C. E., Jerrett, M., Tager, I. B., Petersen, M. L., Mann, J. K., & Balmes, J. R. (2016b). Differential respiratory health effects from the 2008 northern California wildfires: A spatiotemporal approach. *Environmental Research*, *150*, 227–235. https://doi.org/10.1016/j.envres.2016.06.012

Richmond-Bryant, J., & Long, T. C. (2020). Influence of exposure measurement errors on results from epidemiologic studies of different designs. *Journal of Exposure Science and Environmental Epidemiology*, *30*(3), 420–429. https://doi.org/10.1038/s41370-019-0164-z

Roth, G. A., Dwyer-Lindgren, L., Bertozzi-Villa, A., Stubbs, R. W., Morozoff, C., Naghavi, M., et al. (2017). Trends and patterns of geographic variation in cardiovascular mortality among US counties, 1980-2014. *JAMA*, *317*(19), 1976–1992. https://doi.org/10.1001/jama.2017.4150

Schranz, C. I., Castillo, E. M., & Vilke, G. M. (2010). The 2007 San Diego wildfire impact on the emergency department of the University of California, San Diego hospital system. *Prehospital and Disaster Medicine*, *25*(5), 472–476. https://doi.org/10.1017/S1049023X0000858X

Smith, M. L., & Chi, G. (2023). Spatial proximity to wildfires as a proxy for measuring $PM_{2.5}$: A novel method for estimating exposures in rural settings. *The Journal of Climate Change and Health*, *11*, 100219. https://doi.org/10.1016/j.joclim.2023.100219

Stowell, J. D., Geng, G., Saikawa, E., Chang, H. H., Fu, J., Yang, C.-E., et al. (2019). Associations of wildfire smoke $PM_{2.5}$ exposure with cardiorespiratory events in Colorado 2011–2014. *Environment International*, *133*, 105151. https://doi.org/10.1016/j.envint.2019.105151

10.1029/2023GH000860

U.S. Census Bureau. (2016). 2016: American community survey 5-year estimates data profiles (excel data file). Retrieved from https://data.census.gov/table?g=050XX00US37021,37039,37043,37075,37087,37089,37099,37111,37113,37115,37121,37149,37161,37173,37175,37199&tid=ACSDP5Y2016.DP05

U.S. Census Bureau. (2022). *Median household income (in 2021 dollars), 2017-2021 (data table)*. Quick Facts. Retrieved from https://www.census.gov/quickfacts/fact/map/NC/INC110221

US Environmental Protection Agency. (2023). NAAQS table (other policies and guidance). Retrieved from https://www.epa.gov/criteria-air-pollutants/naaqs-table

Wang, S. V., Coull, B. A., Schwartz, J., Mittleman, M. A., & Wellenius, G. A. (2011). Potential for bias in case-crossover studies with shared exposures analyzed using SAS. *American Journal of Epidemiology*, *174*(1), 118–124. https://doi.org/10.1093/aje/kwr038

Wilkins, J. L., Pouliot, G., Pierce, T., Soja, A., Choi, H., Gargulinski, E., et al. (2022). An evaluation of empirical and statistically based smoke plume injection height parametrisations used within air quality models. *International Journal of Wildland Fire*, *31*(2), 193–211. https://doi.org/10.1071/WF20140

WNC Health Network. (N.D.). WNC healthy impact | hospital & public health agency partnership network | about. WNC health network. Retrieved from https://www.wnchn.org/wnc-data/