Wildfire exposure and health care use among people who use durable medical equipment in Southern California

Heather McBrien1

Sebastian Rowland1

Tarik Benmarhnia2

Benjamin Steiger1

Sara Tartof3

Joan A. Casey1

### Abstract

**Background:** Wildfires cause stress and injury in affected communities while exposing 70% of the US population to wildfire fine particulate matter (PM2.5) annually. Few studies examine wildfire smoke exposure in vulnerable populations, such as those using electricity-dependent durable medical equipment (DME) or evaluate residence near fires or in evacuation zones as risk factors for healthcare utilization.

**Methods:** We linked daily counts of residential Zip Code Tabulation Area (ZCTA) level outpatient, inpatient, and emergency department healthcare visits, made from 2016-2020 by DME-using Kaiser Permanente members 45 or older, to daily estimates of ZCTA-level wildfire generated PM2.5 and maps of ZCTAs evacuated during the 2018 and 2019 Woolsey and Getty fires. We performed negative binomial regression to evaluate direct and lagged effects of wildfire PM2.5 on healthcare visit frequency and analogous difference-in-differences analyses to evaluate fire and evacuation exposure.

**Results:** Analyses consisted of 236,732 DME patients in 274 ZCTA groupings. Increased wildfire PM2.5 concentrations (per 10 were associated with a decrease (RR = 0.96, 95% CI: 0.94, 0.99) in outpatient visits one day after exposure and increases on four of the five subsequent days (RR 1.03-1.12). Woolsey Fire exposure was associated with fewer all-cause outpatient visits (RR = 0.87, 95% CI: 0.78, 0.98), but more inpatient visits for cardiorespiratory concerns (RR = 1.45, 95% CI: 1.01, 2.11). Neither Getty Fire proximity nor evacuation from either fire was associated with visit frequency.

**Conclusions:** DME users may have sheltered in place on or after smoky days, and during the Woolsey Fire. However, smoke and the Woolsey Fire may still have produced health concerns in this population particularly vulnerable to wildfire smoke.

# Introduction

Wildfires are widespread, have increased in severity because of climate change, and will worsen in coming decades (Spracklen et al. 2009; Fried, Torn, and Mills 2004; Westerling et al. 2006; Abatzoglou and Williams 2016). The direct impacts of wildfire, such as evacuations, power outages, and destruction of infrastructure cause trauma, stress, financial strain, and physical injury in affected communities (Belleville, Ouellet, and Morin 2019; McCaffrey Sarah 2014). 70% of the US population is exposed to wildfire smoke annually as winds blow smoke over major cities (Jia Coco Liu et al. 2016; O’Dell et al. 2021; Lassman et al. 2017).

Among other components harmful to health, wildfire smoke contains fine particulate matter (PM2.5). Wildfire PM2.5 often consists of more organic carbon and elemental carbon, meaning wildfire PM2.5 may be more or less harmful than other PM2.5 from other sources (Nakayama Wong et al. 2011; Aguilera, Corringham, Gershunov, and Benmarhnia 2021; Peng et al. 2021). It also constitutes most extreme PM2.5 exposure in California, accounting for 71% of total PM2.5 on days that exceed US Environmental Protection Agency (USEPA) daily standard of 12 (Jia Coco Liu et al. 2016).

Wildfire PM2.5 exposure has been associated with adverse mental health and birth outcomes (Reid et al. 2016), but most studies examining wildfire PM2.5 exposure have focused on respiratory and cardiovascular disease. Exposure has been associated with asthma and COPD symptom exacerbation (Colleen Reid 2019; Anjali Haikerwal and Dennekamp 2015; Yao et al. 2020), increases in ED and inpatient visits related to cardiorespiratory disease (Reid et al. 2019; Hutchinson et al. 2018, Reid et al. 2016; Jia Coco Liu et al. 2017), and increased mortality (Kollanus et al. 2016; Doubleday et al. 2020; Jia C. Liu et al. 2015).

While the health consequences of wildfire smoke exposure are well examined in general populations, few studies have examined smoke exposure in vulnerable populations (Jia Coco Liu et al. 2017; Ian P. Davies 2018; Rappold et al. 2017; Aguilera, Corringham, Gershunov, Leibel, et al. 2021), or focused on non-smoke wildfire exposures. Only descriptive research has documented the effects of stress, evacuation, property destruction, or injury due to wildfire disasters (Belleville, Ouellet, and Morin 2019; McCaffrey Sarah 2014; Dodd et al. 2018). We hypothesize this second exposure pathway, based on proximity to wildfire, operates primarily through stress.

The Woolsey Fire burned around 400km2 from November 8th to 21st, 2018 in Los Angeles and Ventura counties, destroying 1643 structures, displacing 295,000 people, and killing three (Los Angeles Fire Department 2018; Matt Styles 2018; “Woolsey Fire Death Toll” 2019). Similarly, the Getty Fire necessitated evacuations in densely populated Los Angeles, as it burned 3km2 from October 28th to November 5th, 2019 (Los Angeles Fire Department 2019). Previously described health effects of similar disasters (Belleville et al. 2019; McCaffery 2014; Christanson 2019) may be even more significant in vulnerable populations.

Here, we evaluate exposure to wildfire through both conventional wildfire PM2.5 concentrations, and through measuring wildfire evacuation and residence within 20km of an active fire. We evaluate the effects of PM2.5 and these novel exposures on healthcare utilization among people who use electricity-dependent durable medical equipment (DME) (Casey et al., 2021).

DME use is common among older adults and is associated with respiratory illness and other disabilities (Jacobs and Lee 2014). “Around 60% of Californian DME renters insured by Medicaid use either Bilevel Positive Airway Pressure (BiPAP) machines, enteral feeding machines, hospital beds, infusion pumps, oxygen equipment, suction pumps, ventilators, or wheelchairs” (Casey et al. 2021). Those with DME-related disabilities may therefore be more vulnerable to stress because of co-occurring medical conditions such as cardiovascular disease or have more difficulty evacuating disaster zones because of limited mobility or need for electricity access (Casey et al. 2021; Kivimaki 2018). Additionally, prior studies have found elevated effect estimates between wildfire smoke exposure and respiratory and cardiovascular disease outcomes among older adults compared to younger populations (Mahsin, Cabaj, and Saini 2021; Anjali Haikerwal and Dennekamp 2015).

Here, we use Kaiser Permanente electronic health record data on DME users from seven Southern California counties from 2016 to early 2020 to examine healthcare utilization during two major wildfire events, and after wildfire PM2.5 exposure throughout the study period.

# Methods

## Study population and outcome data

We used electronic health record data from Kaiser Permanente Southern California to identify all individuals who were 45 or older as of October 29th, 2019, and had rented DME in the year prior. We obtained daily counts of healthcare visits by this population at the Zip Code Tabulation Area (ZCTA) level, in seven counties in Southern California from January 1st, 2016 to March 15th, 2020. Specifically, we obtained counts of all-cause outpatient visits, all-cause emergency department (ED) visits, and all-cause inpatient admissions, as well as ED visits and inpatient admissions specifically for circulatory or respiratory disease outcomes (identified using *International Classification of Diseases* 10 codes I00-I99 and J00-J99, respectively). 236,732 DME patients lived in the study area, which covered most of San Bernardino, Orange, Los Angeles, Riverside, San Diego, Ventura, and Kern counties (**Figure 1**). The area consisted of 582 ZCTAs, each containing 1-1773 patients. During 2018 and 2019, these seven counties experienced 23 wildfires that burned over 4 km2 in California (Cal Fire Incident Archive 2018, 2019).

The Columbia Institutional Review Board determined this study was not human subjects research.

## Exposure Definition

### Wildfire PM2.5

We measured wildfire smoke exposure by estimating daily wildfire and non-wildfire PM2.5 concentrations at the ZCTA level using a multistage approach. Briefly, we identified smoke-plume exposed ZCTA codes/days with the National Oceanic and Atmospheric Administration’s (NOAA) Hazard Mapping System (HMS) and overall PM2.5 concentrations with USEPA monitoring data from the….sentence here about what we did…. To estimate daily ZCTA-level wildfire and non-wildfire PM2.5 concentrations. See ‘Tarik’s paper’ for a more detailed description of our estimation methods.

Daily healthcare visit counts by ZCTA were low and often zero (median outpatient visits = 1 (IQR = 3), median ED and inpatient visits = 0, IQR = 0). To address this and avoid zero-inflation in our models, we could have aggregated ZCTA counts to the weekly level. However, prior studies of wildfire smoke exposure have found associations between same-day air pollution and healthcare visits over the course of the following week (Reid et al. 2019; Hutchinson et al. 2018, Reid et al. 2016; Jia Coco Liu et al. 2017). To evaluate a lagged effect in our data, we required daily healthcare visit counts, therefore, we opted to aggregate our data into higher-level spatial groupings of several ZCTAs based on spatial proximity (**Appendix Methods 1**). We calculated daily wildfire and non-wildfire PM2.5 by averaging concentrations across higher-level ZCTA groupings (hereafter ZCTA groupings).

### Evacuation and proximity to wildfire

To measure direct exposure to wildfire, we obtained data on the fire boundaries and evacuation zones of two significant Southern California wildfires – the Woolsey Fire and the Getty Fire. The Woolsey Fire, which burned from November 8th, 2018 until November 21st, 2018, required the evacuation of 295,000 people in the study area, from Los Angeles and Ventura counties. It burned 1643 structures and almost 400 km2 of land, making it particularly destructive (Los Angeles Fire Department 2018; Matt Styles 2018; “Woolsey Fire Death Toll” 2019). The Getty Fire, which ignited on October 28th, 2019 and burned until November 5th, 2019, was notable because it necessitated evacuations during its 9-day duration in densely populated Los Angeles (Los Angeles Fire Department 2019). Additionally, the Thomas Fire burned over 1100 km2 during our study period, (National Interagency Fire Center 2018), but in the more rural northern corner of Ventura county, and outside the study area. Therefore, we did not include the Thomas Fire in the proximity analyses, but smoke from this fire contributed significantly to wildfire PM2.5 in Ventura County in December 2017 (**Figure 2**).

We obtained shapefiles of the total areas burned during the Getty and Woolsey fires from the CAL FIRE Fire and Resource Assessment Program (FRAP 2018). Fire boundaries expanded while the fires were active, but dynamic fire boundary data was not available. We therefore used total burned areas to identify ZCTAs within 20km of the fire boundary. Machine-readable data on evacuation zones for either fire was not available, though there were several maps available of evacuation zones at different timepoints during each fire. We reviewed webpages (**Appendix Methods 2**) containing maps of the evacuation zones and traced what we believe is an accurate boundary around all areas ever evacuated during each fire in QGIS (QGIS Software 2009) (**Figure 1**). Using these data, we considered ZCTAs proximal (i.e., exposed) to either fire if they were within 20 km of the final fire boundary, and evacuated if they were within 10 km of any evacuation zone (**Figure 1**). We added these 10km and 20km buffers around each zone since fire, evacuation, and anticipating potential fire or evacuation can all cause stress (Belleville, Ouellet, and Morin 2019; McCaffrey Sarah 2014; Dodd et al. 2018).

For analysis, we aggregated daily visit counts to the weekly level. This aggregation removed weekend-weekday patterns in outpatient visits and prevented zero inflation. We considered a week exposed if the Woolsey or Getty fire burned any day that week.

## Analysis

We used negative binomial regression to evaluate the relationship between daily wildfire PM2.5 and daily ZCTA grouping-level healthcare visit counts. We ran analyses for five different healthcare visit types: all-cause outpatient, ED, and inpatient visits, and ED and inpatient visits for circulatory or respiratory disease endpoints. We were interested in lagged effects of wildfire PM2.5 on healthcare visits. We examined the autocorrelation of wildfire PM2.5 concentrations and found only weak autocorrelation (lags 1-7 days had <0.25 correlation with lag 0). This is unlike other sources of air pollution; wildfire PM2.5 concentrations increased dramatically on certain days but then decreased just as quickly (**Figure 2**). We therefore did not constrain our models, and instead included fixed effects for wildfire PM2.5 lags 0-7 days. We also performed an additional analysis examining weekly wildfire PM2.5 levels lagged up to two weeks.

To evaluate evacuation and proximity to wildfire, we used a difference-in-differences (DID) analysis with negative binomial regression to estimate the associations between evacuation and wildfire proximity and weekly ZCTA-level healthcare visit counts, again evaluating five types of visits. We evaluated each relationship separately for each exposure and each fire, performing 20 regression analyses in R (R Core Team 2021) using the mgcv package (Wood 2017). The DID estimators subtracted the change in visit frequency during a fire among ZCTAs far from the fire or evacuation zone (difference 1) from the change in visit frequency during a fire among ZCTAs exposed to the fire or evacuation zone (difference 2). If all models were specified correctly and parallel trends conditions were met, the DID estimator corresponded to the difference in visit frequency attributable to direct wildfire exposure. We assessed the parallel trends assumption visually (Appendix B).

We included offsets accounting for population exposed in both sets of models, and controlled for temperature using a penalized spline term, as temperature can predict respiratory and cardiovascular healthcare utilization (Rochelle S. Green 2010) and wildfire (Vlassova et al. 2014), using daily temperature data from the PRISM Climate Group (PRISM Climate Group 2021). In the wildfire PM2.5 concentration models, we controlled for daily temporal effects with a natural spline term and in the proximity models we controlled for weekly temporal effects with a penalized spline term. We used the number of years in the study period (four) to determine the natural spline flexibility (12 degrees of freedom). In the PM2.5 concentration models, we controlled for non-wildfire PM2.5, and added a fixed effect for weekends to the outpatient visits model, accounting for fewer visits on weekend days. We did not control for wildfire PM2.5 in the wildfire proximity models, as we considered this a mediator rather than a confounder.

To account for correlation between ZCTA groupings, we included fixed effects for a comprehensive set of socioeconomic variables, obtaining values by ZCTA from the 5-year 2015-2019 ACS (U.S. Census Bureau 2016-2020). We included median income, home ownership (% homes occupied by owner), poverty (percent households below threshold income), age structure (percent of population under 5, 5-19, 20-64, and 65+ years), and racial/ethnic structure (percent Hispanic, percent non-Hispanic white, percent non-Hispanic Black). We took a simple mean within ZCTA groupings to obtain average covariate values by ZCTA grouping or summed within ZCTA groupings when appropriate.

We tested both wildfire proximity, evacuation, and PM2.5 results for sensitivity to parameterization of splines, by re-running all analyses with natural splines in place of penalized splines, described in appendix C. See <https://github.com/heathermcb/wildfires_DME> for all analysis code and model equations.

# Results

## Health data description

The 236,732 patients renting DME from Kaiser Permanente Southern California from January 1, 2016 to March 15th, 2020 had a daily average of 2.5 (SD = 4.7) outpatient visits, 0.1 (SD = 0.5) ED visits, and 0.1 (SD = 0.4) inpatient visits per ZCTA grouping. There were on average 8 (SD = 8.9) outpatient visits per week per ZCTA, 0.5 (SD = 1.5), ED visits, and 0.2 (SD = 0.8) inpatient visits. The most common diagnoses were for circulatory or respiratory disease: of the 62,892 ED visits made over the study period, 49,364 (78%) were for circulatory or respiratory disease concerns, as were 30,325 (90%) of inpatient visits.

## PM2.5 exposure

Mean daily wildfire PM2.5 concentration by ZCTA grouping throughout the study period was 0.22 (SD = 2.67) (**Figure 2**), since most groupings on most days (85% of days) had 0 wildfire PM2.5. The maximum concentration was 551.53 . Mean daily non-wildfire PM2.5 by grouping was 11.00 (SD = 6.69), just under the annual USEPA exposure limit of 12 . On the 366 days when wildfire PM­2.5 was non-zero in any grouping, the mean concentration in ZCTA groupings with non-zero measurements was 5.6(SD = 12.1).

214 of the 274 ZCTA groupings experienced daily mean non-wildfire PM­­­2.5 concentrations greater than the USEPA daily limit of 35 during the study period. During 10% of study period days (n=156) at least one ZCTA grouping exceeded the USEPA daily limit based on non-wildfire PM2.5 concentrations. In contrast, only on 1.3% of days (n=21) did at least one ZCTA grouping exceed the limit based on wildfire PM2.5, meaning most above-limit levels were attributable to non-wildfire PM2.5. On days where wildfire PM2.5 exceeded USEPA limits, in ZCTA groupings over the limit, wildfire PM2.5 made up 91% of total PM2.5.

In adjusted negative binomial models, a 10 increase in wildfire PM2.5 was associated with a decrease in outpatient visits one day later, RR = 0.96, 95% CI: 0.94, 0.99), with 6 days, and increases on four of the five subsequent days, with rate ratios ranging from 1.03-1.12 (**Table 1a**). Wildfire PM2.5 levels were not associated with the frequency of ED visits, inpatient visits, ED visits for cardiorespiratory concerns, and inpatient visits for cardiorespiratory concerns.

In our additional analysis examining weekly wildfire PM2.5 levels lagged up to two weeks, a 10 increase in weekly PM2.5 was associated with a same-week increase in outpatient visits (RR = 1.10, 95% CI: 1.04, 1.17), consistent with the daily outpatient visit model. Additionally, there were increases in weekly outpatient visits one and two weeks later **(Table something)**. Weekly PM2.5 levels were not associated with the frequency of any other visits.

## Proximity to wildfire

There were 54 ZCTAs within 20 km of the Woolsey Fire boundary, and so exposed to the fire. Despite the comparatively small size of the Getty Fire (~3 km2 vs ~400 km2), 98 ZCTAs were exposed, as the Woolsey Fire was more rural. 21 and 20 ZCTAs were evacuated during the Getty and Woolsey fires respectively, and all evacuated ZCTAs were within 20km of the fire boundary, meaning that the evacuated ZCTAs were a subset of those close to the fire in both cases.

### Woolsey evacuation and fire exposure

Throughout the study period (not specifically during the fire), we observed elevated counts of all types of healthcare visits in the ZCTAs located within 20 km of the Woolsey Fire. During the Woolsey Fire, the frequency of all types of visits increased by 15 to 22% across the whole study area, except outpatient visits, which remained the same. Woolsey Fire proximity during the fire was associated with decreased outpatient visits, and increased inpatient admissions for cardiorespiratory disease (**Table 1b**).

Similarly, throughout the study period, we observed elevated visit counts of all types of healthcare visits in ZCTAs evacuated during the fire, and during the fire, the frequency of all types of visits increased throughout the study area, except for outpatient visits. However, evacuation from the Woolsey Fire was not associated with frequency of any kind of healthcare visit. (TABLE SOMETHING.)

### Getty Fire exposure

Like the Woolsey Fire, we observed elevated counts of outpatient visits in ZCTAs located within 20 km of the Getty Fire versus those located outside this area (RR = 1.04, 95% CI: 1.03, 1.06), as well as all-cause ED visits and ED visits for cardiorespiratory concerns (RR = 1.10, 95% CI: 1.07, 1.14 and RR = 1.18, 95% CI: 1.14, 1.22, respectively) (**Table 1b**). The frequency of other visits did not differ between ZCTAs that would and would not be exposed. During the Getty Fire, outpatient visits, ED visits, and ED visits for cardiorespiratory problems increased across the entire study area (RR = 1.12, 95% CI: 1.07, 1.17, RR = 1.23, 95% CI: 1.10, 1.38, RR = 1.23, 95% CI: 1.08, 1.38, respectively), but there was no additional increase in ZCTAs exposed to the fire.

Similarly, there were more outpatient, all-cause ED visits and ED visits for cardiorespiratory concerns in ZCTAs located in the Getty evacuation zone than those outside of it, and increases in outpatient, all-cause ED, and ED visits for cardiorespiratory problems during the Getty Fire. There were no additional increases in visits in ZCTAs evacuated during the fire. (TABLE SOMEHTING).

# Discussion

Using electronic health data on 236,732 Kaiser Permanente DME patients from 2016-2020, we found that 10 increases in wildfire PM2.5 were associated with next-day decreases in outpatient visits made by older adult DME users, and increases in outpatient visits up to three weeks after a change. Increases in wildfire PM2.5 were not associated with the frequency of other visits. We also observed an association between residential proximity to the Woolsey Fire and fewer all-cause outpatient visits, as well as more frequent cardiorespiratory inpatient visits (RR = 0.87, 95% CI: 0.87, 0.98; RR = 1.45, 95% CI: 1.01, 2.11 respectively). Our study was unique in that we evaluated healthcare utilization in a group hypothesized to be susceptible to disaster and wildfire smoke exposures, and we examined residence near a wildfire or in an evacuation zone.

There is a strong relationship between wildfire smoke exposure and cardiorespiratory health described in the literature (Reid et al. 2016). The majority of studies measure this association through healthcare utilization and find increases in hospital admissions and ED visits for cardiorespiratory outcomes following wildfire PM2.5, PM10, or general smoke exposure (Henderson et al. 2011; Thelen et al. 2013; Delfino et al. 2009; Morgan et al. 2010). Large population-level studies confirm these results (Ye et al. 2021; Johnston et al. 2014).

Fewer studies have examined wildfire PM2.5 exposure in vulnerable populations (Reid et al. 2019; Xi et al. 2020). Of studies examining older adults, all have reported associations between smoke exposure and increased healthcare visit frequency (DeFlorio-Barker et al. 2019; Ignotti et al. 2010; Morgan et al. 2010; Henderson et al. 2011), and while some studies find older adults at elevated risk compared to younger adults (Ignotti et al. 2010; Delfino et al. 2009; Haikerwal et al. 2015), others find the converse (Rappold et al. 2011; Henderson et al. 2011).

Limited studies have assessed outpatient care utilization during smoke exposure and most have focused on outpatient visits for respiratory concerns, reporting increases during smoke exposure, (Sheldon and Sankaran 2017; Lee et al. 2009; Moore et al. 2006; Mott et al. 2002). None of those studies examined all-cause outpatient care use. Only Hutchinson et al. 2018 simultaneously reported decreases in all-cause outpatient visits during smoke exposure and increases in visits for respiratory concerns only.

Surprisingly, we observed no association between wildfire PM2.5 and ED or inpatient visits. We observed an initial next-day decrease in all-cause outpatient visits, and then observed a positive association between wildfire PM2.5 and outpatient visits among DME users for the three weeks following exposure. We hypothesized that older adult DME users would be particularly susceptible to wildfire PM­2.5 due to probable high rates of underlying cardiorespiratory disease (Jacobs and Lee 2014). Our outpatient visit findings are consistent with much of the literature and this hypothesis. However, the null association we observed in the rest of the analyses is surprising, especially given increased outpatient care use by this population. DME users especially vulnerable to smoke may be sheltering in place during smoky periods or taking other precautions, or limitations may be obscuring associations between smoke and more urgent healthcare use.

Few studies have evaluated proximity to wildfire boundaries or wildfire evacuation as risk factors for healthcare utilization or adverse health outcomes (Binet et al. 2021; Park et al. 2021; Tally et al. 2013). Proximity to wildfires can affect health through a stress pathway, as well as through air pollution. Qualitative studies emphasize this point, and several have documented the immense stress experienced by those displaced by wildfire (Belleville et al. 2019; McCaffery 2014; Christanson 2019). After the 2014 Northwest Territory wildfires, one interviewee said: “Well, it took a toll on me because being stressed out from the fires and never knowing when we had to leave to be evacuated we didn’t know if we were going to come home to a community or to our houses” (Dodd et al. 2018). Additionally, a 2021 study evaluated the likely prevalence of Post-Traumatic Stress Disorder among Canadian Fort McMurray wildfire survivors at 12.8%, twice the baseline population prevalence (Agyapong et al. 2021). We attempted to assess this pathway for two major fires in our study area using a difference-in-differences analysis. We found no association between exposure and healthcare visits during the Getty Fire. However, during the Woolsey Fire, we observed an increase in all-cause and cardiorespiratory inpatient visits and a decrease in all-cause outpatient visits. The 400 km2 Woolsey Fire, which caused $3 billion in damages, was so much larger than the 3 km2  Getty Fire, which destroyed 10 homes, that null associations between Getty proximity exposure and all visit types could be due to its smaller size. A larger analysis examining several wildfires, rather than two, could be informative.

Study limitations could have influenced our results. First, we only had access to data on visits to Kaiser Permanente clinics and hospitals made by Kaiser members using DME. These patients would be highly motivated to seek care at Kaiser, given their insurance status, however they may have sought urgent care for PM2.5-related needs at other clinics. This could have produced artificially reduced visit counts, especially inpatient and emergency visit counts in which we did not observe any changes, during smoke exposure. Similarly, outpatient care decreases during the Woolsey Fire could be explained by patients visiting other, non-Kaiser Permanente clinics or hospitals when they evacuated.

Second, the wildfire PM2.5 concentrations estimated here were interpolated using measured total PM2.5 concentrations and images of wildfire smoke plumes. This correctly excluded non-wildfire smoke PM2.5 (e.g., smoke from agricultural burning) from wildfire PM2.5 concentration estimates. However, this non-wildfire smoke may have affected healthcare use in the same way as wildfire PM2.5. For example, the highest daily ZCTA grouping PM2.5 concentration in the study was recorded in Kern county and was the result of an agricultural burn. The county-level increase in non-wildfire PM2.5 can be seen in **Figure 2**: while non-wildfire PM2.5 remains low in Ventura County in December 2017 during the Thomas Fire, it is extremely high in Kern County due to these agricultural burns. These high levels of non-wildfire PM2.5 may have weakened the observed statistical relationship between wildfire PM2.5 and healthcare use in our study. In addition, inpatient and ED visits were much less frequent over the study period than outpatient visits. It’s possible our PM2.5 models were underpowered to detect changes in these visits.

We did not assess differences in healthcare use by type of DME or stratify by age group or sex beyond limiting our study population to those age 45 or older. This excluded most breast pump users, a healthy subpopulation who constitute 30% of DME users of all ages at Kaiser Permanente (Casey et al. 2021). Subgroups such as those using ventilators or those using breast pumps likely have vastly different health needs and outcomes. We chose to focus on DME users aged 45 and older who were likely the most susceptible to wildfire.

**Conclusion**

This study found an association between elevated wildfire PM2.5 concentration and all-cause outpatient visits. However, we found no relationship between elevated wildfire PM2.5 and inpatient or ED visits. DME users especially vulnerable to smoke may be sheltering in place during smoky periods or taking other precautions, or our study may be underpowered to detect true associations.

Decreased outpatient healthcare utilization among DME users living close to wildfires suggests that wildfire disaster may interrupt routine care. While we saw a small increase in inpatient visits related to wildfire proximity, we saw no relation with elevated wildfire PM2.5­ and either ED or inpatient visits.

As wildfires become more frequent and severe with climate change, we must understand how they affect both local populations and those exposed to wildfire PM2.5. Protecting vulnerable populations that may be harmed by exposures which others can avoid or endure is essential. More work is needed to understand how DME users respond to wildfires, and how we can best support those affected by smoke, fire, and evacuation.

# Appendix

## Notes on wildfire evacuation zones, boundaries, and exposure definition

We reviewed the following webpages containing maps of the evacuation zones, and traced what we believed to be an accurate boundary around all areas evacuated in each fire in QGIS (QGIS Software 2009). The evacuation zone boundaries we defined are plotted in Figure 1, along with the fire boundaries. Our code is available at <https://github.com/heathermcb/kaiser_wildfires>.

| Getty Fire: |
| --- |
| 1. <https://www.newsweek.com/getty-fire-evacuation-map-update-california-los-angeles-1468222> |
| 1. <https://www.newsweek.com/getty-center-fire-map-evacuation-los-angeles-california-1468100> |
| 1. <https://www.express.co.uk/news/world/1196943/getty-fire-evacuation-map-405-fire-update-los-angeles-fire-evacuation-road-school-closures> |
| 1. <https://www.flyertalk.com/forum/los-angeles/1993097-getty-fire-405-closed-sepulveda-pass-now-open.html> |
| 1. <https://heavy.com/news/2019/10/getty-fire-los-angeles/> |

| Woolsey Fire: |
| --- |
| 1. <https://www.kclu.org/local-news/2018-11-10/map-shows-boundaries-of-woolsey-hill-brush-fires-and-evacuation-areas> |
| 1. <https://wildfiretoday.com/tag/woolsey-fire/> |
| 1. <https://www.dailynews.com/2018/11/08/this-map-shows-where-the-hill-fire-and-woolsey-fire-are-burning/> |
| 1. <https://www.mercurynews.com/2018/11/09/map-of-woolsey-and-hill-fires-highway-101-closed-malibu-evacuated/> |
| 1. <https://woolseylawyers.com/woolsey-fire-map/> |

## Higher-level groupings of ZCTAs

We created higher-level groupings of ZCTAs using the numerical ZCTA codes. We used a bespoke method, and then tested the resulting spatial groupings to make sure that ZCTAs grouped together had similar exposure measurements, to guard against exposure misclassification. We grouped ZCTAs together if all their numerical codes differed by 1 in sequence. For example, codes 90001-90008 and 90011-90014 were in the study area. We grouped codes 90001 - 90008 together, as they are all sequentially 1 digit apart, while 90011-90014 formed a second grouping. This method resulted in groupings of ZCTAs that were all adjacent, since similar codes tend to be geographically close.

Using this method, we created 274 groups containing 1-19 ZCTAs each, with a mean and mode group size of 2. We assessed the correlation between wildfire PM2.5 within each group and between all ZCTAs regardless of group, concluding that wildfire PM2.5 measurements within groups were highly correlated (mean within-group correlation was r = 0.96), while mean correlation of PM2.5 between any two ZCTAs was 0.48. We also mapped the groups to confirm that all ZCTAs grouped together were adjacent. The code that creates these groupings and assesses them is available at <https://github.com/heathermcb/kaiser_wildfires>.

# References

Abatzoglou, John T, and A Park Williams. 2016. “Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests.” *Proc Natl Acad Sci U S A* 113 (42): 11770–75.

Aguilera, Rosana, Thomas Corringham, Alexander Gershunov, and Tarik Benmarhnia. 2021. “Wildfire Smoke Impacts Respiratory Health More Than Fine Particles from Other Sources: Observational Evidence from Southern California.” *Nature Communications* 12 (1): 1493.

Aguilera, Rosana, Thomas Corringham, Alexander Gershunov, Sydney Leibel, and Tarik Benmarhnia. 2021. “Fine Particles in Wildfire Smoke and Pediatric Respiratory Health in California.” *Pediatrics* 147 (4).

Agyapong, Vincent IO, et al. "Prevalence rates and correlates of likely post-traumatic stress disorder in residents of fort mcmurray 6 months after a wildfire." *International Journal of Mental Health and Addiction* 19.3 (2021): 632-650.

Anjali Haikerwal, Anthony Del Monaco, Muhammad Akram, and Martine Dennekamp. 2015. “Impact of Fine Particulate Matter (PM 2.5) Exposure During Wildfires on Cardiovascular Health Outcomes.” *JAHA*.

Belleville, Genevieve, Marie-Christine Ouellet, and Charles M. Morin. 2019. “Post-Traumatic Stress Among Evacuees from the 2016 Fort McMurray Wildfires: Exploration of Psychological and Sleep Symptoms Three Months After the Evacuation.” *International Journal of Environmental Research and Public Health* 16 (9).

Binet, Émilie, et al. "A portrait of mental health services utilization and perceived barriers to care in men and women evacuated during the 2016 Fort McMurray Wildfires." *Administration and Policy in Mental Health and Mental Health Services Research* (2021): 1-13.

US Census Bureau. 2016-2020. “American Community Survey 5-Year Public Use Samples,” 2016-2020.

California Department of Forestry and Fire Protection Fire and Resource Assessment Program (FRAP). <https://frap.fire.ca.gov/>. 2018.

Cal Fire Incident Archive. 2018. “Getty Fire Incident.” 2018.

———. 2019. “Woolsey Fire Incident.” 2019.

Casey, Joan A, Marriele Mango, Seth Mullendore, Mathew V Kiang, Diana Hernández, Bonnie H Li, Kris Li, Theresa M Im, and Sara Y Tartof. 2021. “Trends from 2008 to 2018 in Electricity-Dependent Durable Medical Equipment Rentals and Sociodemographic Disparities.” *Epidemiology* 32 (3): 327–35.

Christianson, Amy Cardinal, and Tara K. McGee. "Wildfire evacuation experiences of band members of Whitefish Lake First Nation 459, Alberta, Canada." *Natural Hazards* 98.1 (2019): 9-29.

Colleen Reid, Melissa May Maestas. 2019. “Wildfire Smoke Exposure Under Climate Change.” *Pulmonary Medicine*.

DeFlorio-Barker, Stephanie, et al. "Cardiopulmonary effects of fine particulate matter exposure among older adults, during wildfire and non-wildfire periods, in the United States 2008–2010." *Environmental health perspectives* 127.3 (2019): 037006.

Delfino, Ralph J., et al. "The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003." *Occupational and environmental medicine* 66.3 (2009): 189-197.

Dodd, Warren, et al. "Lived experience of a record wildfire season in the Northwest Territories, Canada." *Canadian Journal of Public Health* 109.3 (2018): 327-337.

Doubleday, Annie, Jill Schulte, Lianne Sheppard, Matt Kadlec, Ranil Dhammapala, Julie Fox, and Tania Busch Isaksen. 2020. “Mortality Associated with Wildfire Smoke Exposure in Washington State, 2006-2017: A Case-Crossover Study.” *Environ Health* 19 (1): 4.

Fried, Jeremy S., Margaret S. Torn, and Evan Mills. 2004. “The Impact of Climate Change on Wildfire Severity: A Regional Forecast for Northern California.” *Climatic Change* 64 (1): 169–91.

Henderson, Sarah B., et al. "Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort." *Environmental health perspectives* 119.9 (2011): 1266-1271.

Hutchinson, Justine A, Jason Vargo, Meredith Milet, Nancy H F French, Michael Billmire, Jeffrey Johnson, and Sumi Hoshiko. 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 Med* 15 (7): e1002601.

Ian P. Davies, James C. Robertson, Ryan D. Haugo. 2018. “The Unequal Vulnerability of Communities of Color to Wildfire.” *PLOS ONE*.

Ignotti, Eliane, et al. "Impact on human health of particulate matter emitted from burnings in the Brazilian Amazon region." *Revista de saude publica* 44 (2010): 121-130.

Jacobs, Bret C., and Justin A. Lee. "Durable medical equipment: Types and indications." *Medical Clinics* 98.4 (2014): 881-893.

Johnston FH, Purdie S, Jalaludin B, Martin KL, Henderson SB, Morgan GG. 2014. Air pollution events from forest fires and emergency department attendances in Sydney, Australia 1996–2007: a case-crossover analysis.Environ Health13:105, doi:10.1186/1476-069X-13-10525491235.

Kivimaki, Steptoe, M. 2018. “Effects of Stress on the Development and Progression of Cardiovascular Disease.” *Nat Rev Cardiol*.

Kollanus, Virpi, Pekka Tiittanen, Jarkko V Niemi, and Timo Lanki. 2016. “Effects of Long-Range Transported Air Pollution from Vegetation Fires on Daily Mortality and Hospital Admissions in the Helsinki Metropolitan Area, Finland.” *Environ Res* 151 (November): 351–58.

Lassman, William, Bonne Ford, Ryan W. Gan, Gabriele Pfister, Sheryl Magzamen, Emily V. Fischer, and Jeffrey R. Pierce. 2017. “Spatial and Temporal Estimates of Population Exposure to Wildfire Smoke During the Washington State 2012 Wildfire Season Using Blended Model, Satellite, and in Situ Data.” *GeoHealth* 1 (3): 106–21.

Lee TS, Falter K, Meyer P, Mott J, Gwynn C. 2009. Risk factors associated with clinic visits during the 1999 forest fires near the Hoopa Valley Indian Reservation, California, USA.Int J Environ Health Res19:315-32719629821.

Liu, Jia Coco, Loretta J Mickley, Melissa P Sulprizio, Francesca Dominici, Xu Yue, Keita Ebisu, Georgiana Brooke Anderson, Rafi F A Khan, Mercedes A Bravo, and Michelle L Bell. 2016. “Particulate Air Pollution from Wildfires in the Western US Under Climate Change.” *Clim Change* 138 (3): 655–66.

Liu, Jia Coco, Ander Wilson, Loretta J. Mickley, Keita Ebisu, Melissa P. Sulprizio, Yun Wang, Roger D. Peng, Xu Yue, Francesca Dominici, and Michelle L. Bell. 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): 730–35.

Liu, Jia C, Gavin Pereira, Sarah A Uhl, Mercedes A Bravo, and Michelle L Bell. 2015. “A Systematic Review of the Physical Health Impacts from Non-Occupational Exposure to Wildfire Smoke.” *Environ Res* 136 (January): 120–32.

Los Angeles Fire Department. 2018. “LAFD News: Getty Fire.” 2018.

Mahsin, M D, Jason Cabaj, and Vineet Saini. 2021. “Respiratory and cardiovascular condition-related physician visits associated with wildfire smoke exposure in Calgary, Canada, in 2015: a population-based study.” *International Journal of Epidemiology*, September.

Matt Styles, Joseph Sterna. 2018. “Woolsey Fire Response Hurt by Poor Disaster Preparation, Lack of Firefighters, Report Says.” 2018.

McCaffrey Sarah, Stidham Melanie, Rhodes Alan. 2014. “Wildfire Evacuation and Its Alternatives: Perspectives from Four United States’ Communities.” *International Journal of Wildland Fire* 24: 170–78.

Moore D, Copes R, Fisk R, Joy R, Chan K, Brauer M. 2006. Population health effects of air quality changes due to forest fires in British Columbia in 2003: estimates from physician-visit billing data.Can J Public Health97:105-10816619995.

Morgan G, Sheppeard V, Khalaj B, Ayyar A, Lincoln D, Jalaludin Bet al.. 2010. Effects of bushfire smoke on daily mortality and hospital admissions in Sydney, Australia.Epidemiology21:47-5519907335.

Mott JA, Mannino DM, Alverson CJ, Kiyu A, Hashim J, Lee Tet al.. 2005. Cardiorespiratory hospitalizations associated with smoke exposure during the 1997 Southeast Asian Forest Fires.Int J Hyg Environ Health208:75-8515881981.

Nakayama Wong, L. S., H. H. Aung, M. W. Lamé, T. C. Wegesser, and D. W. Wilson. 2011. “Fine Particulate Matter from Urban Ambient and Wildfire Sources from California’s San Joaquin Valley Initiate Differential Inflammatory, Oxidative Stress, and Xenobiotic Responses in Human Bronchial Epithelial Cells.” *Toxicology in Vitro* 25 (8): 1895–905.

O’Dell, Katelyn, Kelsey Bilsback, Bonne Ford, Sheena E. Martenies, Sheryl Magzamen, Emily V. Fischer, and Jeffrey R. Pierce. 2021. “Estimated Mortality and Morbidity Attributable to Smoke Plumes in the United States: Not Just a Western US Problem.” *GeoHealth* 5 (9): e2021GH000457.

Park, Bo Young, et al. "The association between wildfire exposure in pregnancy and foetal gastroschisis: A population‐based cohort study." *Paediatric and perinatal epidemiology* 36.1 (2022): 45-53.

PRISM Climate Group. 2021. “PRISM Climate Group Daily Temperature Data.” 2021.

“QGIS Software.” 2009. <http://qgis.org>.

R Core Team, 2021. <https://www.R-project.org/>.

Rappold, Ana G., Jeanette Reyes, George Pouliot, Wayne E. Cascio, and David Diaz-Sanchez. 2017. “Community Vulnerability to Health Impacts of Wildland Fire Smoke Exposure.” *Environmental Science & Technology* 51 (12): 6674–82.

Rappold, Ana G., et al. "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 (2011): 1415-1420.

Reid, Colleen E, Michael Brauer, Fay H Johnston, Michael Jerrett, John R Balmes, and Catherine T Elliott. 2016. “Critical Review of Health Impacts of Wildfire Smoke Exposure.” *Environ Health Perspect* 124 (9): 1334–43.

Reid, Colleen E, Ellen M Considine, Gregory L Watson, Donatello Telesca, Gabriele G Pfister, and Michael Jerrett. 2019. “Associations Between Respiratory Health and Ozone and Fine Particulate Matter During a Wildfire Event.” *Environ Int* 129 (August): 291–98.

Rochelle S. Green, Brian Malig, Rupa Basu. 2010. “The Effect of Temperature on Hospital Admissions in Nine California Counties.” *International Journal of Public Health* 55: 113–21.

Sheldon, Tamara L., and Chandini Sankaran. "The impact of Indonesian forest fires on Singaporean pollution and health." *American Economic Review* 107.5 (2017): 526-29.

Spracklen, D. V., L. J. Mickley, J. A. Logan, R. C. Hudman, R. Yevich, M. D. Flannigan, and A. L. Westerling. 2009. “Impacts of Climate Change from 2000 to 2050 on Wildfire Activity and Carbonaceous Aerosol Concentrations in the Western United States.” *Journal of Geophysical Research: Atmospheres* 114 (D20).

Tally, Steven, et al. "The impact of the San Diego wildfires on a general mental health population residing in evacuation areas." *Administration and Policy in Mental Health and Mental Health Services Research* 40.5 (2013): 348-354.

Thelen, Brian, et al. "Modeling acute respiratory illness during the 2007 San Diego wildland fires using a coupled emissions-transport system and generalized additive modeling." *Environmental Health* 12.1 (2013): 1-22.

Vlassova, Lidia, Fernando Perez-Cabello, Marcos Rodrigues Mimbrero, Raquel Montorio Lloveria, and Alberto Garcia-Martin. 2014. “Analysis of the Relationship Between Land Surface Temperature and Wildfire Severity in a Series of Landsat Images.” *Remote Sensing* 6 (7): 6136–62.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. “Warming and Earlier Spring Increase Western u.s. Forest Wildfire Activity.” *Science* 313 (5789): 940–43.

Wood, Simon. 2017. *Generalized Additive Models: An Introduction with r*. 2nd ed. Chapman; Hall/CRC.

“Woolsey Fire Death Toll.” 2019. <https://www.mercurynews.com/2018/11/14/woolsey-fire-death-toll-increases-to-3-lasd-investigating/>.

Xi, Yuzhi, et al. "Mortality in US hemodialysis patients following exposure to Wildfire smoke." *Journal of the American Society of Nephrology* 31.8 (2020): 1824-1835.

Yao, Jiayun, Michael Brauer, Julie Wei, Kimberlyn M McGrail, Fay H Johnston, and Sarah B Henderson. 2020. “Sub-Daily Exposure to Fine Particulate Matter and Ambulance Dispatches During Wildfire Seasons: A Case-Crossover Study in British Columbia, Canada.” *Environ Health Perspect* 128 (6): 67006.

Ye, Tingting, et al. "Risk and burden of hospital admissions associated with wildfire-related PM2· 5 in Brazil, 2000–15: a nationwide time-series study." *The Lancet Planetary Health* 5.9 (2021): e599-e607.