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

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### Abstract

**Background:** Climate change-induced wildfires cause trauma, 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, or evaluate residence in evacuation zones as risk factors for healthcare utilization.

**Methods:** We identified Kaiser Permanente Southern California members aged 45 or older who used electricity-dependent durable medical equipment (DME) in 2019. DME use is associated with respiratory illness and disability, indicating vulnerability to smoke exposure and potential difficulty evacuating disaster zones. Daily counts of residential Zip Code Tabulation Area (ZCTA) code-level outpatient, inpatient, and emergency department healthcare visits by DME users from 2016-2020 were linked with daily estimates of ZCTA-level wildfire generated PM2.5, and ZCTAs evacuated during the 2019 and 2018 Getty and Woolsey fires. We performed negative binomial regression using direct and lagged effects of wildfire PM2.5 and difference-in-differences analyses to evaluate the association between wildfire evacuation exposure and healthcare visit frequency, adjusting for individual and area-level confounders.

**Results:** Analyses consisted of 236,732 DME patients living in 582 ZCTAs, aggregated to 274 groupings. 10 increases in wildfire PM2.5 concentrations were associated with 1-13% decreases in outpatient visits for the subsequent six days. Likewise, Woolsey Fire proximity exposure was associated with fewer all-cause outpatient visits (RR = 0.87, 95% CI: 0.78, 0.98), however, it was also associated with more inpatient visits for cardiorespiratory concerns (RR = 1.45, 95% CI: 1.01, 2.11). Getty Fire proximity exposure was not associated with visit frequency.

**Conclusions:** DME users, presumed vulnerable to wildfire smoke exposure, may have sheltered in place on smoky days or took other precautions. However, the Woolsey Fire, at nearly 400 km2 and 100 times larger than the Getty, may have produced health concerns in those directly affected when evacuation was necessary and sheltering in place impossible.

# 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). Winds also move smoke plumes across continents, exposing major cities and 70% of the US population to wildfire smoke annually (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 is likely more harmful to health than PM2.5 from other sources (Nakayama Wong et al. 2011; Aguilera, Corringham, Gershunov, and Benmarhnia 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) standards (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 cardiorespiratory symptom exacerbation (Colleen Reid 2019; Anjali Haikerwal and Dennekamp 2015; Yao et al. 2020), increases in outpatient, ED, and inpatient visits related to these conditions (Reid et al. 2019; Hutchinson et al. 2018, Reid et al. 2016; Jia Coco Liu et al. 2017), and increased mortality from these conditions (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). This second exposure pathway, based on proximity to wildfire, may operate primarily through stress. For example, 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). Similarly, 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). Direct exposure to these disasters could produce significant health effects, especially in vulnerable populations.

Here, we evaluate both exposure to wildfire through more conventional wildfire PM2.5 concentrations, as well as through proximity to wildfire, and measure the effect of these 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 estimate the association between healthcare use by DME users and two separate exposures: residential proximity to wildfire and wildfire PM2.5­ concentration. We identified 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. In 2018 and 2019 respectively, these seven counties experienced 10 and 13 wildfires which 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’ and TARIK CITATION. 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 more than a week later (Reid et al. 2019; Hutchinson et al. 2018, Reid et al. 2016; Jia Coco Liu et al. 2017). To test for 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).

### Proximity to wildfire

To measure proximity to wildfire, we obtained data on the fire boundaries and evacuation zones of two significant Southern California wildfires: the Getty Fire and the Woolsey Fire. The Getty Fire, which ignited on October 28th, 2019 and burned until November 5th, 2019, is notable because it necessitated evacuations in the study area during its 9-day duration, in densely populated Los Angeles (Los Angeles Fire Department 2019). Similarly, 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 Thomas Fire also burned during our study period, and was larger than the Getty Fire (National Interagency Fire Center 2018). However, it burned in the rural northern corner of Ventura county, and outside the study area in Santa Barbara county, so we did not include it in the proximity analyses, but smoke from this fire contributed significantly to wildfire PM2.5 in the study area (**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 exposed ZCTAs. The Woolsey Fire burned for 13 days, so ZCTAs that were close to the fire boundary and marked as ‘exposed’ in our study may not have been close to the fire at first, and only truly exposed later.

Just as the fire boundaries changed, evacuation zones also changed throughout each fire. 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 believed to be an accurate boundary around all areas ever evacuated in each fire in QGIS (QGIS Software 2009) (**Figure 1**). Using these data, we considered ZCTAs proximal to either fire if they were within 20 km of the final fire boundary or within 10 km of any evacuation zone (**Figure 1**). We considered evacuated ZCTAs, those close to the evacuation zone, and those close to the fire all exposed, since fire, evacuation, and anticipating potential fire or evacuation can cause stress (Belleville, Ouellet, and Morin 2019; McCaffrey Sarah 2014; Dodd et al. 2018).

As in the previous analysis, the number of DME-using patients in each ZCTA ranged from 1 – 1773 (median = 488.5, IQR = 875.5), and the number of daily health care visits by ZCTA was often low or zero (median outpatient visits = 1 (IQR = 3), median ED and inpatient visits = 0, IQR = 0). However here, to avoid zero-inflation, we aggregated daily visit counts to the weekly level. This aggregation also removed weekend-weekday patterns in outpatient visits. We considered weeks exposed if the fire burned any day that week.

## Analysis

We used negative binomial regression to test the relationship between daily wildfire PM2.5 and daily ZCTA grouping-level healthcare visit counts. We tested 5 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 sharply (**Figure 2**). We therefore did not constrain our models, and instead included fixed effects for wildfire PM2.5 lags 0-7 days.

To evaluate proximity to wildfire, we used a difference-in-differences (DID) analysis with negative binomial regression to estimate the association between wildfire proximity and weekly ZCTA-level healthcare visit counts, again testing 5 types of visits. We tested each relationship separately for both the Getty and Woolsey Fires, performing ten 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 (difference 1) from the change in visit frequency during a fire among ZCTAs exposed to the fire (difference 2). We checked the parallel trends assumption with plots, included in appendix B. If all models were specified correctly and the parallel trends assumption holds, the DID estimator corresponded to the difference in visit frequency attributable to direct wildfire exposure.

We included offsets accounting for exposed population size in both sets of models, and controlled for temperature using a penalized spline term, as temperature can be a predictor of respiratory and cardiovascular healthcare utilization (Rochelle S. Green 2010) and wildfire (Vlassova et al. 2014), using daily temperature data from the PRISM Climate Group website (PRISM Climate Group 2021). We controlled for weekly temporal effects in the proximity models again with a penalized spline term, while in the wildfire PM2.5 concentration models, we controlled for daily temporal effects with a natural spline term. We used the number of years in the study period (four) to determine the appropriate spline flexibility (12 degrees of freedom). In the PM2.5 concentration models, we controlled for non-wildfire PM2.5, and added a fixed effect 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.

In the wildfire PM2.5 models, we intended to include a random effect to account for variation between ZCTA groupings, but limited computational power prevented it. Instead, 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 when appropriate, or summed within ZCTA groupings when appropriate. See <https://github.com/heathermcb/kaiser_wildfires> for all analysis code and model equations.

# Results

## Health data description

The 236,732 patients renting DME from Kaiser Permanente Southern California during the 1561-day study period made 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 = 0.83) 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 very low at 0.22 (SD = 2.67) since most groupings on most days (85% of days) reported 0 wildfire PM2.5, while the maximum concentration was extremely high at 551.53 . However, mean daily non-wildfire PM2.5 by grouping (calculated by subtracting wildfire PM2.5 measurements from estimates of total) was 11.0 (SD = 6.69), just under the annual USEPA exposure limit of 12 . On the 366 days when wildfire PM­2.5 was non-zero, mean concentrations in ZCTA groupings with non-zero measurements was 5.6(SD = 12.1). See **Figure 2** for mean PM2.5 concentrations in the study area by county.

214 of the 274 ZCTA groupings experienced daily mean non-wildfire PM­­­2.5 concentrations greater than the USEPA daily limit of 35 at some point. There were 156 days of the 1561 studied where at least one grouping experienced above-limit non-wildfire PM2.5. In contrast, only 42 groupings experienced above-limit wildfire PM2.5, on 21 days, 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 present.

10 increases in wildfire PM2.5 were associated with decreases in outpatient visits lasting 6 days, with rate ratios ranging from 0.87 to 0.99 (see **Table 1a** for all RRs and CIs). The effects were almost constant over the period of 6 days. The frequency of ED visits, inpatient visits, ED visits for cardiorespiratory concerns, and inpatient visits for cardiorespiratory concerns did not change with changes in wildfire PM2.5. 10 increases in wildfire PM2.5 were associated with a very small decrease in all inpatient admissions lagged by 3 days (RR = 0.86, 95% CI: 0.75, 0.98), however, lags 0-2 and 4-6 were not significant, and showed no sub-significant pattern of increase or decrease towards lag 3. Similarly, ED visits decreased slightly in frequency six days after increases in wildfire PM2.5 (for a 10 increase, RR = 0.88, 95% CI: 0.80, 0.98), while all other lags were insignificant.

## Proximity to wildfire

There were 98 ZCTAs exposed to the Getty Fire: within 20 km of the Getty Fire boundary, in an evacuated area, or within 10 km of an evacuated area. Despite the comparatively large size of the Woolsey Fire (~100,000 acres vs. ~800 acres), only 54 ZCTAs were exposed, as the Woolsey Fire was more rural.

### Getty Fire exposure

Throughout the study period (not specifically during the fire), we observed elevated counts of outpatient visits in ZCTAs located in the Getty Fire exposure zone versus those located outside of it (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) (**Table 1b**), but there was no additional increase in ZCTAs exposed to the fire (see **Table 1b**  for RRs and CIs).

### Woolsey Fire exposure

Like the Getty Fire, all types of healthcare visits were more frequent in the ZCTAs located in the Woolsey Fire exposure zone during the entire study period (RR = 1.15, 95% CI: 1.14, 1.17; RR = 1.13, 95% CI: 1.08, 1.18; RR = 1.10, 95% CI: 1.04, 1.17; RR = 1.16, 95% CI: 1.11, 1.21; RR = 1.12, 95% CI: 1.05, 1.18; for all outpatient, ED, inpatient visits and cardiorespiratory ED and inpatient visits, respectively). During the Woolsey Fire, the frequency of all types of visits increased by 15 to 22% across the study area (**Table 1b**), except outpatient visits, which remained the same (RR 1.01, 95% CI: 0.97, 1.04). Proximity to the Woolsey Fire during the fire was not associated with changes in all-cause or cardiorespiratory ED visits, or all-cause inpatient visits. However, Woolsey Fire exposure was associated with decreased all-cause outpatient visits and increased cardiorespiratory inpatient visits (RR = 0.87, 95% CI: 0.87, 0.98; RR = 1.45, 95% CI: 1.01, 2.11).

# Discussion

Using electronic health data on 236,732 Kaiser Permanente DME patients from 2016-2020, we 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). 10 increases in wildfire PM2.5 were associated with 1-13% decreases in outpatient visits for six days after a change, and were not associated with other types of healthcare visits. Our study was unique in that we evaluated healthcare utilization among DME patients, a group hypothesized to be susceptible to disaster and wildfire smoke exposures, and we examined exposure to evacuation from wildfire.

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 found associations between smoke exposure and increased healthcare utilization (DeFlorio-Barker et al. 2019;, Ignotti et al. 2010; Morgan et al. 2010; Henderson et al. 2011), however some find older adults are more at risk than younger adults (Ignotti et al. 2010; Delfino et al. 2009; Haikerwal et al. 2015), while others find the converse (Rappold et al. 2011; Henderson et al. 2011).

The literature examining outpatient care utilization during smoke exposure is also limited. While several studies have looked at outpatient visits made only for respiratory concerns, and found 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, and an inverse association with outpatient visits among DME users. We hypothesized that older adult DME users would be particularly susceptible to wildfire PM­2.5 due to probable high rates of underlying cardiorespiratory disease, as these diseases can be indications for DME use (Jacobs and Lee 2014). It is possible DME users are more cognizant of wildfires, reduce activities, and shelter in their homes, thereby protecting themselves from wildfire smoke. However, Casey et al. 2021 showed that DME users were no more prepared for power outages than other groups including wildfire-related outages. Whether DME users are more prepared for wildfires remains unclear.

Though our findings are surprising, they are consistent with Hutchinson et al., who found reduced outpatient visits during wildfire PM2.5 exposure. It is possible that all-cause outpatient visits may usually be less frequent during smoke exposure in most populations, but such reductions are not described in the literature because most studies do not examine all-cause outpatient care.

Few studies have evaluated proximity to wildfire boundaries as a risk factor 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), and a 2021 study evaluated the prevalence of PTSD among Canadian Fort McMurray wildfire survivors at 12.8% (Agyapong et al. 2021). We assessed 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 did observe an increase in all-cause and cardiorespiratory inpatient visits and a decrease in outpatient visits. The Woolsey Fire burned almost 400 km2, destroyed 1643 structures, and displaced 295,000 people, causing $3 billion in damages. In contrast, the Getty burned only 3km2 and destroyed 10 homes. Because the Woolsey Fire was so much larger than the Getty Fire, null associations between Getty proximity exposure and all visit types could be because of its smaller size. A larger analysis examining several wildfires, rather than two, could shed light on this issue.

Limitations could also explain these results. First, we only had access to data on visits to Kaiser 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 it is possible that they sought urgent care for PM2.5-related needs at other clinics. This could produce artificially reduced visit counts during smoke exposure. Similarly, outpatient care during the Woolsey Fire could be explained 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 wildfire PM2.5 did. 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 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.

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 all DME users (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 likely more vulnerable to wildfire.

**Conclusion**

This study found reduced outpatient healthcare utilization among DME users exposed to elevated levels of wildfire PM2.5 and wildfire proximity, suggesting wildfire disaster may interrupt important routine care. While we saw a small uptick in inpatient visits related to wildfire proximity, we saw no relation with elevated wildfire PM2.5­ and either ED or inpatient visits, suggesting this group has also successfully sheltered in place on poor air quality days.

As wildfires become more frequent and severe with climate change, we must understand how they affect both local populations and those exposed to smoke. 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 user 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. As always, 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>.

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