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# Effects of fine particulate matter from wildfire and non-wildfire sources on emergency-department visits in people who were housed and unhoused in San Diego County (CA, USA) during 2012–20: a time-stratified case–crossover study

Lara Schwarz, Andrew Nguyen, Emilie Schwarz, Edward M Castillo, Jesse J Brennan, Theodore C Chan, Rosana Aguilera, Alexander Gershunov, Tarik Benmarhnia



## Summary

**Background** Being unhoused can increase vulnerability to adverse health effects due to air pollution. We aimed to quantify changes in emergency-department visits during and after exposure to wildfire-specific and non-wildfire particulate matter  $2.5\ \mu\text{m}$  or less in diameter ( $\text{PM}_{2.5}$ ) in San Diego County (CA, USA) in people who were both unhoused and housed.

**Methods** For this time-stratified case–crossover study, we used data on exposure to wildfire-specific  $\text{PM}_{2.5}$  in California and individual-level data for people admitted to the emergency departments of two hospitals (UC San Diego Health emergency departments at La Jolla and Hillcrest, San Diego) in San Diego County between July 1, 2012, and Dec 31, 2020. People with a postcode outside of San Diego County were excluded. Demographic information was age group, race or ethnicity, and transport to the emergency department. Wildfire-specific  $\text{PM}_{2.5}$  concentration at the postcode level was previously estimated using an ensemble model that combined multiple machine-learning algorithms and explanatory variables obtained via data on 24-h mean  $\text{PM}_{2.5}$  concentrations from the US Environmental Protection Agency Air Quality System. Conditional logistic regression models were applied, adjusting for specific humidity, wind velocity, and maximum temperature extracted from the US Gridded Surface Meteorological Dataset. Housing status was established by registration staff or triage nurses on arrival at the emergency department. For people who were unhoused, exposure was defined based on the weighted mean  $\text{PM}_{2.5}$  concentration at the city level proportional to the number of people who were unhoused in each specific city across urban centres in San Diego County. For people who were housed, we used residence postcode to measure exposure. We assessed the association between  $\text{PM}_{2.5}$  from wildfire and non-wildfire sources and emergency-department visits in people who were housed and unhoused.

**Findings** There were 587 562 emergency-department visits at the two hospitals, 76 407 (13.0%) of which were by people who were unhoused. People who were housed had a higher exposure to overall  $\text{PM}_{2.5}$  (24-h mean over the study period of  $9.904\ \text{mg}/\text{m}^3$ , SD  $3.445$ ) and non-wildfire  $\text{PM}_{2.5}$  ( $9.663$ ,  $2.977$ ) than people who were unhoused ( $9.863$ ,  $3.221$ ;  $9.557$ ,  $2.599$ ). However, people who were unhoused had a higher exposure to wildfire-specific  $\text{PM}_{2.5}$  ( $0.305$ ,  $1.797$ ) than people who were housed ( $0.240$ ,  $1.690$ ). Overall  $\text{PM}_{2.5}$  exposure was associated with increased odds of emergency-department visits for both people who were housed (odds ratio  $1.003$ , 95% CI  $1.001$ – $1.004$  per  $1\ \mu\text{g}/\text{m}^3\ \text{PM}_{2.5}$  for 0–3 days after exposure) and people who were unhoused ( $1.004$ ,  $1.000$ – $1.008$  for 0–3 days after exposure). We found that non-wildfire  $\text{PM}_{2.5}$  was associated with emergency-department visits among people who were housed ( $1.003$ ,  $1.002$ – $1.005$  for 0–3 days after exposure) and wildfire-specific  $\text{PM}_{2.5}$  was associated with emergency-department visits in people who were unhoused ( $1.006$ ,  $1.001$ – $1.011$  for 0–3 days after exposure).

**Interpretation** People who were unhoused in San Diego County were more likely to visit emergency departments after exposure to increased wildfire-specific  $\text{PM}_{2.5}$ . As the intensity and frequency of wildfires increase, understanding risk factors for vulnerable populations, such as people who are unhoused, is crucial to develop effective adaptation strategies.

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## Introduction

Wildfires are an increasing challenge to public health and source of air pollution, eroding decades of air

pollution-reduction measures, such as the Clean Air Act, in the west of the USA.<sup>1</sup> Although wildfires can be a naturally occurring part of ecosystem renewal, the

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**Research in context****Evidence before this study**

In many parts of the world, homelessness is one of the most pressing societal issues and climate change is the most pressing environmental concern. Wildfire frequency is increasing and wildfires are becoming a substantial source of air pollution in many regions, yet little is known about the health effects of wildfire smoke on people who are unhoused. We searched Google Scholar for papers published in English from database inception to Feb 17, 2021, using the terms “homeless” OR “unhoused” AND “wildfire smoke” OR “air pollution” AND “health”. We conducted the same search from database inception to Feb 1, 2024, to update our findings. There was some research into the adverse effects of outdoor air pollution on people who are unhoused. However, to our knowledge, no research has evaluated the effect of wildfire smoke, which affects health differently.

**Added value of this study**

To our knowledge, this is the first epidemiological study to quantify the health effects of wildfire-specific particulate

matter  $\leq 2.5 \mu\text{m}$  in diameter ( $\text{PM}_{2.5}$ ) on people who are unhoused. We found that this population had a higher exposure to wildfire-specific  $\text{PM}_{2.5}$  than people who were housed and that exposure was associated with higher odds of visiting hospital emergency departments 0–3 days after a wildfire event.

**Implications of all the available evidence**

Air pollution from wildfires will only become more severe with continuing climate change. Understanding the specific vulnerability factors of people who are unhoused can help develop and inform interventions and action plans. Our findings can be used to prioritise this vulnerable group when developing and implementing public health protection measures during wildfires, and future research should continue exploring the risk of being unhoused in the contexts of climate and social change.

frequency and intensity of these fires in the USA has steadily increased with the changing climate.<sup>2</sup> With this increase in frequency comes an increase in air pollution. For example, particulate matter (PM), carbon monoxide, nitrogen oxide, ozone, and non-methane organic compounds are wildfire byproducts that are of public health concern.<sup>3</sup> Inhalation of these pollutants negatively affects cardiovascular function, propagates oxidative stress on the respiratory system, and predisposes the respiratory system to reduced operational capacity.<sup>4</sup> Of particular concern is fine PM (ie,  $\text{PM}_{\leq 2.5 \mu\text{m}}$  in diameter [ $\text{PM}_{2.5}$ ]), which penetrates the body deeply (ie, enters the bloodstream and crosses the blood–brain barrier to affect neurological functioning) and is potentially more harmful when sourced from wildfires than from other, non-wildfire sources due to a higher composition of polar organic compounds and free radicals.<sup>5,6</sup> Exposure to wildfire smoke is estimated to account for approximately 300 000 annual deaths worldwide.<sup>7</sup>

The largest wildfires in coastal southern California, USA, are typically spread by the first Santa Ana winds of the season, which often start in October before the first rains of winter.<sup>8,9</sup> Wind-driven rural wildfires burn intensely and spread quickly, producing  $\text{PM}_{2.5}$  that is more dangerous to human health than similar amounts of  $\text{PM}_{2.5}$  from other sources, such as traffic or industry.<sup>5</sup>

The negative health effects of exposure to wildfire smoke can be exacerbated by social factors. Previous literature has suggested associations between low socioeconomic status, older age, minoritised race or ethnicity, and less education and increased exposure to wildfire smoke, exposure to air pollutants, and adverse

health effects in the USA.<sup>10,11</sup> Low access to preventive health care and resources to mitigate and protect against these exposures can also increase vulnerability to the health effects of wildfire smoke. In the USA, areas of land most vulnerable to wildfires are disproportionately populated by people of minoritised race or ethnicity.<sup>12</sup> Moreover, people with pre-existing cardiorespiratory conditions are more susceptible to wildfire smoke.<sup>13</sup> Documenting who is most vulnerable to wildfire-smoke exposure is crucial in adequately informing appropriate public health responses and interventions. However, research into differing vulnerability to air pollution, including from wildfires, does not include some of the most marginalised groups in the USA, such as people who are unhoused.

Low socioeconomic status, minoritised race or ethnicity, and pre-existing health conditions are often seen in people who are unhoused or who do not have access to stable, safe, and clean housing. In California, USA, an estimated 150 000 people were unhoused in 2022; 30% of all people who were unhoused in the USA lived in the state at the time, including half of all people who were unsheltered.<sup>14</sup> This population disproportionately includes people of minoritised race or ethnicity.<sup>14</sup> Generally, in the USA, people who are unhoused are more vulnerable to poor health conditions and increased all-cause mortality rates than people who are housed.<sup>15</sup> Evidence from different regions worldwide has shown that exposure to extreme weather is associated with increased depression, mortality, risk of hospitalisation, visits to the emergency department, and substance use in people who are unhoused.<sup>16–20</sup>

People who are unhoused might be particularly vulnerable to air pollutants and wildfire smoke; they have less access to health care, have higher rates of mental ill health, and are more consistently exposed to harsh climate and environmental conditions without access to indoor shelter than people who are housed.<sup>19</sup> However, research into the health effects of air quality and wildfire-smoke exposure in this population is scarce. Studies that have explored the effects of air pollution in people who are unhoused show an increased risk of exposure. For example, a survey in Tulare County (CA, USA) showed that people who were unhoused spent a large amount of time in close proximity to pollution sources, such as busy roads.<sup>21</sup> Moreover, interviews with people who were unhoused in Salt Lake County (UT, USA) revealed a relationship between poor air quality and poor health outcomes, such as discomfort, headaches, and stress.<sup>22</sup>

External public health threats can compound these poor health outcomes. In 2020 in California, many people who were unhoused had to practise physical distancing during the COVID-19 pandemic while seeking shared shelter from smoke and ash generated from a destructive wildfire season.<sup>23</sup> People without climate-controlled shelter are most at risk of the concurrent and compound effects of high heat and air-pollution exposure.<sup>24</sup> Although there are little epidemiological data on poor health outcomes due to air pollution and wildfire smoke in people who are unhoused in the USA, the need to obtain and understand such data is pressing due to the rapidly expanding homelessness and environmental crises in the country. Challenges in obtaining these data include exposure attribution and scarce data collection regarding housing status.<sup>21,22,24</sup>

Understanding which populations are particularly vulnerable to air pollution and wildfire smoke is crucial as they can be prioritised in interventions to improve public health. Fortunately, there are some existing systems that could inform effective strategies. For example, an early-warning smoke-forecasting system in British Columbia, Canada, could predict respiratory health effects from wildfires.<sup>25</sup> Furthermore, cooling centres in 20 US jurisdictions extended sheltering for people who are unhoused during high-heat days.<sup>26</sup> Data on the vulnerability of people who are unhoused to wildfire smoke can be used to coordinate public health messaging on smoke-related hazards and clean-air shelters (ie, indoor spaces with increased filtration capacity that are opened to the public).

San Diego County is one of the areas in the USA with the most people who are unhoused, the number of whom has increased by 14% between 2022 and 2023.<sup>27</sup> Moreover, San Diego County has had some of the greatest wildfire-related destruction in the past 40 years.<sup>28</sup> Exposure to wildfire-specific PM<sub>2.5</sub> has also been increasing in the USA, estimated to account for up to half of overall PM<sub>2.5</sub> exposure in western regions.<sup>29</sup> Of all the counties in

California, San Diego has the highest respiratory acute-care use that is attributable to wildfire smoke.<sup>30</sup>

We aimed to quantify changes in emergency-department visits during and after exposure to wildfire-specific PM<sub>2.5</sub> in San Diego County in people who were both unhoused and housed. We also aimed to evaluate the risk of emergency-department visits associated with PM<sub>2.5</sub> exposure from both wildfire and non-wildfire sources and to explore vulnerability factors that could increase the risk of emergency-department visits related to air pollution in people who were unhoused. We hypothesised that people who were unhoused would be more susceptible to PM<sub>2.5</sub> from wildfire and non-wildfire sources than people who were housed.

## Methods

### Study design

For this time-stratified case–crossover study,<sup>31</sup> we used modelled data on wildfire-specific PM<sub>2.5</sub> in California and individual-level data on the housing status of people admitted to the emergency departments of two hospitals in San Diego County (UC San Diego Health emergency departments at La Jolla and Hillcrest, San Diego, CA, USA) between July 1, 2012, and Dec 31, 2020.

The study received ethical approval from the University of California San Diego (San Diego, CA, USA; institutional review board number 811055).

### Data sources

Individual-level data for people admitted to emergency departments were from the two hospitals in San Diego County, which had a shared patient population and electronic medical-record system (Epic Software, Epic Systems, Verona, WI, USA). People with a postcode outside of San Diego County were excluded.

As this study was a retrospective study using information from electronic medical records, it was deemed exempt from requiring informed consent from participants by the University of California San Diego.

Wildfire smoke particulate matter estimates were obtained from a previous study,<sup>32</sup> in which data from the US Environmental Protection Agency Air Quality System were used to estimate 24-h mean PM<sub>2.5</sub> concentration at the postcode level using an ensemble model. A multiple-imputation approach with random forest was used to estimate counterfactual PM<sub>2.5</sub> concentrations that would have been observed in the absence of wildfire smoke (ie, non-wildfire PM<sub>2.5</sub>), which allowed estimations of 24-h wildfire-specific PM<sub>2.5</sub> at the postcode level.<sup>32</sup>

Other environmental variables were specific humidity (ie, the amount of water vapour contained in a unit of air), wind velocity, and maximum temperature, which we extracted from the US Gridded Surface Meteorological Dataset.<sup>33</sup> Specific humidity has shown similar correlations to health-related outcomes as other water vapour-mass based metrics (eg, relative humidity).<sup>34</sup>

For the Air Quality System see <https://www.epa.gov/airs>

For the Gridded Surface Meteorological Dataset see <https://www.drought.gov/data-maps-tools/gridded-surface-meteorological-gridmet-dataset>

## Procedures

Housing status was established by registration staff or triage nurses at arrival to the emergency department on the basis of address, living situation notation, or a secondary diagnosis of homelessness (ICD-10 Z59.0). People were considered to be unhoused if they were experiencing sheltered or unsheltered homelessness at the time of visit. We chose to define people being unhoused if they were experiencing sheltered or unsheltered homelessness to consider both unstable and impermanent access to housing.

Other demographic information was age group (ie, 18–44 years, 45–64 years, or 65 years or older); race or ethnicity (ie, Hispanic or Latino, non-Hispanic Asian, non-Hispanic Black, non-Hispanic White, non-Hispanic other, or unknown), which we used to evaluate whether there was a disproportionate burden for people of minoritised race or ethnicity;<sup>35</sup> and transport to the emergency department (ie, emergency [basic or Basic Life Support ambulance, critical-care transport, paramedic unit, or private ambulance], personal [automobile, public transport, taxi, or walk in], or other [helicopter, military, other, aeroplane, police custody, special transport, or unknown]), which could provide information on resource use during wildfires. Sex or gender data were not used in our dataset.

We considered all-cause visits and cause-specific visits to emergency departments. Cause-specific visits were defined by primary diagnosis (ie, respiratory [ICD-10 J00–J99], cardiovascular [ICD-10 I00–I99], or mental health [ICD-10 F01–F99]).

We used multiple machine-learning algorithms<sup>32</sup> and explanatory variables to estimate 24-h  $PM_{2.5}$  concentrations at the postcode level. We then used a multiple-imputation approach with random forest to estimate counterfactual  $PM_{2.5}$  concentrations that would have been observed in the absence of wildfire smoke (ie, non-wildfire  $PM_{2.5}$ ), which allowed us to estimate 24-h wildfire-specific  $PM_{2.5}$  at the postcode level.<sup>32</sup> Exposure variables were overall  $PM_{2.5}$ , non-wildfire  $PM_{2.5}$ , and wildfire-specific  $PM_{2.5}$ ; this included wildfire smoke from major events in San Diego County during the study period (appendix p 10) as well as any wildfire smoke that affected the region. We evaluated  $PM_{2.5}$  concentrations on the same day as emergency-department visits, during the 3 previous days to consider lagged effects, and the mean average of all 4 days.

To estimate the effects of  $PM_{2.5}$  on people who were unhoused without a residence postcode, we conducted a weighting procedure to weigh wildfire-smoke exposure on the basis of the location of people who were unhoused in San Diego County.<sup>20</sup> Point-in-time counts from the US Department of Housing and Urban Development are a count, annually or every other year, of people who are unhoused on a night in late January; in 2020, this date was Jan 29.<sup>36</sup> These counts are provided at the region level across the USA; we weighted mean average  $PM_{2.5}$  at the city level proportionally to the number of people who

were unhoused in each urban centre (city) in San Diego County. For people who were housed, we used residence postcode to measure exposure.

The primary outcome was all-cause emergency-department visits for people who were housed and people who were unhoused. As a secondary analysis, we explored subdiagnoses and other individual-level risk factors.

## Statistical analysis

We evaluated  $PM_{2.5}$  concentrations on the same day as the emergency-department visit, during the 3 days previous to the emergency-department visit to consider lagged effects, and calculated the mean of all 4 days. A time-stratified case–crossover design was applied to study the association between overall  $PM_{2.5}$ , wildfire-specific  $PM_{2.5}$ , non-wildfire  $PM_{2.5}$ , and emergency-department visits for people who were housed and people who were unhoused.

The time-stratified case–crossover design resembles the design and analysis of a case–control study.<sup>31</sup> Each emergency-department visit was defined as a case, and controls were defined as the 3–4 days that are the same day of the week of the case in the same month and year. Exposure to air pollution for case days was compared with exposure of control days in case–control pairs; this comparison assessed the risk of visits to the emergency department via conditional logistic regression.

We applied a conditional logistic-regression model to explore the association between  $PM_{2.5}$  concentration and emergency-department visits for each exposure. We analysed lagged effects up to 3 days for any short-term delayed effects of wildfire-smoke exposure.<sup>37,38</sup> We applied Cochran Q tests to evaluate heterogeneity between people who were unhoused and housed for each air-pollution exposure. We estimated a ratio of odds ratios (ORs) to compare the association between  $PM_{2.5}$  and emergency-department visits for people who were housed and unhoused. To consider vulnerability factors that might exacerbate the association between air pollution and emergency-department visits for people who were unhoused, we stratified analyses by race or ethnicity, age group, transport to the emergency department, and primary diagnosis.

We excluded any emergency-department visit with a postcode outside of San Diego County or with missing postcode information ( $n=41\,573$ ). Missing demographic data were categorised in a separate group (unknown or other).

We conducted three sensitivity analyses. One considered lagged effects of 4–6 days. The second removed 2020 from the study period due to potentially different health-seeking behaviours during COVID-19. The third was restricted to first-time emergency-department visits to evaluate the potential role of repeated visits.

Stata version 16 and R version 4.0 were used for all analyses.

See Online for appendix

### Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

### Results

After excluding people who were housed with postcodes outside of San Diego County, there were 587 562 emergency-department visits at the two hospitals between July 1, 2012, and Dec 31, 2020, 76 407 (13.0%) of which were by people who were unhoused (table 1). 69 975 (91.6%) of 76 407 visits were by people who were unhoused aged 18–64 years, compared with 395 934 (77.5%) of 511 155 visits by people who were housed aged 18–64 years. 15 302 (20.0%) of 76 407 visits were by people who were unhoused and non-Hispanic Black, compared with 61 310 (12.0%) of 511 155 visits by people who were housed and non-Hispanic Black. However, 11 309 (14.8%) of 76 407 visits were by people who were unhoused and Hispanic or Latino, but in people who were housed, 125 721 (24.6%) of 511 155 visits were from people who were Hispanic or Latino.

People who were housed had a numerically higher exposure to overall  $PM_{2.5}$  and non-wildfire  $PM_{2.5}$  than people who were unhoused (table 2). However, people who were unhoused had a numerically higher exposure to wildfire-specific  $PM_{2.5}$  than people who were housed (table 2). During the study period, people who were housed and who were unhoused were numerically more exposed to  $PM_{2.5}$  on case days than on control days (table 2; figure 1).

Emergency-department visits were more likely for every  $1 \mu\text{g}/\text{m}^3$  increase in overall  $PM_{2.5}$  and non-wildfire  $PM_{2.5}$  for people who were housed at 0–3 days after exposure to air pollution, but we did not identify an increased risk associated with wildfire-specific  $PM_{2.5}$  at any time interval for this group. There were increased odds of emergency-department visits among people who were unhoused for every  $1 \mu\text{g}/\text{m}^3$  increase in overall  $PM_{2.5}$  exposure when averaged over 3 days of exposure, and for wildfire-specific  $PM_{2.5}$  at a 1–2 day lag and averaged over 3 days since the wildfire event (figure 2). For all exposures and time windows the 95% CI of odds ratios in people who are housed and unhoused were overlapping. For people who were unhoused, the highest odds of emergency-department visits were associated with wildfire-specific  $PM_{2.5}$  at 1 day after exposure (OR 1.007, 95% CI 1.001–1.002). For people who were housed, the highest odds were associated with non-wildfire  $PM_{2.5}$  averaged over 3 days after exposure. Associations were similar when removing 2020 and only including first-time visits, although the precision decreased due to smaller sample sizes (appendix pp 2–3). When considering days 4–6 after air-pollution exposure, there was no association between wildfire-specific  $PM_{2.5}$  and emergency-department visits for people who were unhoused (appendix p 4).

	People who were unhoused (n=76 407)	People who were housed* (n=511 155)
<b>Age group</b>		
18–44 years	27 930 (36.6%)	216 319 (42.3%)
45–64 years	42 045 (55.0%)	179 615 (35.1%)
65 years or older	6 432 (8.4%)	115 221 (22.5%)
<b>Transport to the emergency department</b>		
Emergency	40 255 (52.7%)	118 487 (23.2%)
Personal	32 091 (42.0%)	376 163 (73.6%)
Other	4 061 (5.3%)	16 505 (3.2%)
<b>Race or ethnicity</b>		
Non-Hispanic White	42 338 (55.4%)	246 590 (48.2%)
Hispanic or Latino	11 309 (14.8%)	125 721 (24.6%)
Non-Hispanic Black	15 302 (20.0%)	61 310 (12.0%)
Non-Hispanic Asian	401 (0.5%)	35 110 (6.9%)
Non-Hispanic other	5 650 (7.4%)	39 306 (7.7%)
Unknown	1 407 (1.8%)	3 118 (0.6%)

Data are n (%). Sex or gender data were not used in the dataset. \*41 573 people were excluded as they had postcodes outside of San Diego County or missing postcode data.

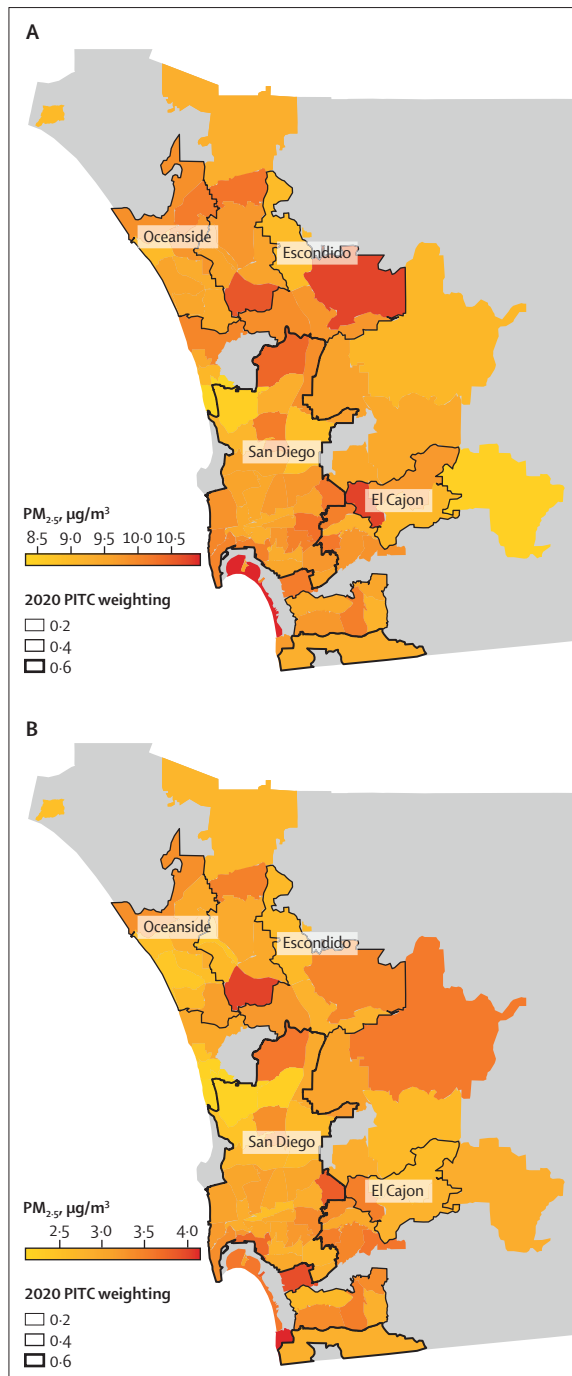
**Table 1: Emergency-department visits of people who were housed and who were unhoused in two hospitals in San Diego County, CA, USA, during 2012–20**

	People who were unhoused (n=76 407)		People who were housed* (n=511 155)	
	Case days (n=76 407)	Control days (n=259 729)	Case days (n=511 155)	Control days (n=1 738 722)
Overall mean $PM_{2.5}$ , $\text{mg}/\text{m}^3$	9.863 (3.221)	9.841 (3.168)	9.904 (3.445)	9.872 (3.411)
Mean non-wildfire $PM_{2.5}$ , $\text{mg}/\text{m}^3$	9.557 (2.599)	9.553 (2.596)	9.663 (2.977)	9.640 (2.983)
Mean wildfire-specific $PM_{2.5}$ , $\text{mg}/\text{m}^3$	0.305 (1.797)	0.289 (1.713)	0.240 (1.690)	0.232 (1.605)
Specific humidity, mass fraction	0.009 (0.003)	0.009 (0.003)	0.009 (0.003)	0.009 (0.003)
Wind velocity, m/s	2.724 (1.063)	2.724 (1.061)	2.708 (1.049)	2.719 (1.067)
Maximum temperature, °C	22.211 (4.342)	22.623 (4.291)	23.460 (5.093)	23.456 (5.102)

Data are mean (SD) and are based on residence postcode for people who were housed and are weighted exposure based on 2020 point-in-time counts for people who were unhoused.  $PM_{2.5}$ =particulate matter  $\leq 2.5 \mu\text{m}$  in diameter. \*41 573 people were excluded as they had postcodes outside of San Diego County or missing postcode data.

**Table 2: Environmental variables in people who were housed and who were unhoused in San Diego County, CA, USA, during 2012–20**

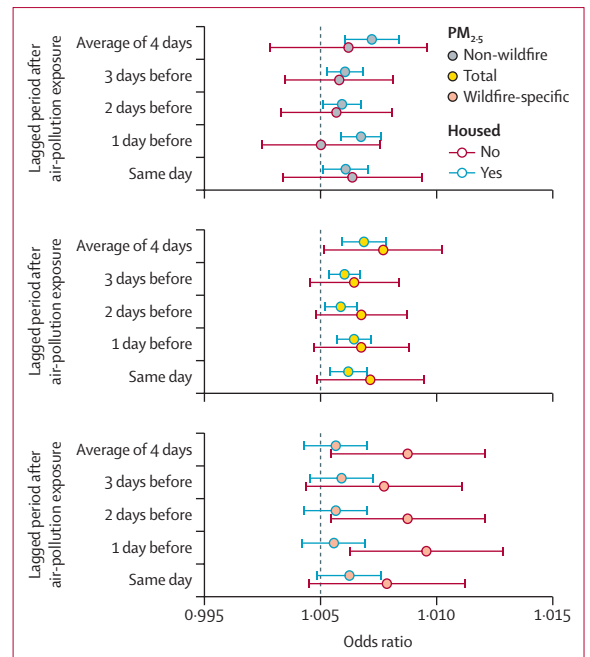
Results from heterogeneity tests revealed the greatest difference between people who were housed and who were unhoused was when wildfire-specific  $PM_{2.5}$  exposure was 1–2 days before emergency-department visit (appendix pp 11, 13). The ratio of odds ratios showed that people who were unhoused had higher odds (OR 1.006, 95% CI 1.001–1.011) of emergency-department visits associated with wildfire-specific  $PM_{2.5}$  the day before the emergency-department visits than people who were housed (appendix p 5). 19.202 (95% CI 5.420–32.409) emergency-department visits per 1000 people were attributable to wildfire-specific  $PM_{2.5}$  the day after exposure in people who were unhoused, compared with 0.034 (0.000–0.116)



**Figure 1:** Mean non-wildfire  $PM_{2.5}$  exposure (A) and wildfire-specific  $PM_{2.5}$  exposure (B) in San Diego County, CA, USA, during 2012–20. Thickness of area outlines denotes the proportion of people who were unhoused in each city based on 2020 point-in-time counts.  $PM_{2.5}$  data are from Aguilera and colleagues.<sup>32</sup> PITC=point-in-time count.  $PM_{2.5}$ =particulate matter  $\leq 2.5\ \mu\text{m}$  in diameter.

emergency-department visits per 1000 people who were housed (appendix p 12).

There were no differences in visits to the emergency department associated with wildfire-specific or



**Figure 2:** Association between overall  $PM_{2.5}$ , wildfire-specific  $PM_{2.5}$ , and non-wildfire  $PM_{2.5}$  per  $1\ \mu\text{g}/\text{m}^3$  and emergency-department visits in people who were housed and who were unhoused in San Diego County, CA, USA, during 2012–20

Time intervals show emergency-department visits on day of air pollution exposure (same day), days after exposure (1–3 days), and mean average during 0–3 days after exposure. Bars show 95% CI.  $PM_{2.5}$ =particulate matter  $\leq 2.5\ \mu\text{m}$  in diameter.

non-wildfire  $PM_{2.5}$  exposure between people who were unhoused by different primary diagnosis (appendix p 6). We also explored potential effect modification by age, race or ethnicity, and transport to the emergency department (appendix pp 7–9), but did not find any significant associations at the 95% confidence level between wildfire exposure and emergency-department visits among people who were unhoused in these stratified analyses, potentially due to small sample size in these subgroups.

### Discussion

People who are unhoused have no access to safe and stable housing to protect against air pollution and wildfire smoke, which can increase their risk of adverse health outcomes. However, to our knowledge, no epidemiological study has quantified the association between wildfire smoke and hospital admissions or emergency-department visits in people who are unhoused. We found that people who were housed and who were unhoused in San Diego County (CA, USA) were both more likely to visit two emergency departments for every  $1\ \mu\text{g}/\text{m}^3$  increase in overall  $PM_{2.5}$ , non-wildfire  $PM_{2.5}$ , and wildfire-specific  $PM_{2.5}$ . However, people who were unhoused showed increased likelihood of emergency-department visits for wildfire-specific  $PM_{2.5}$  and decreased likelihood of emergency-department visits for non-wildfire  $PM_{2.5}$  compared with people who were housed.

Our results suggest a higher vulnerability to wildfire-specific PM<sub>2.5</sub> in people who are unhoused than in people who are housed in San Diego County. Previous observational research in southern California found that wildfire-specific PM<sub>2.5</sub> was up to ten times more harmful to human health than PM from other sources, which have different chemical compositions.<sup>5,39</sup> Although people who are housed might adapt their behaviours during a wildfire by staying indoors and using air-filtration systems, people who are unhoused often do not have access to the same protection measures. People who are unhoused have challenges in accessing air-conditioned spaces during extreme heat due to scarce information, no access to transport, and policies that are not inclusive of their needs;<sup>40</sup> these issues would likely also be challenges during wildfires. Our results indicate that people who are unhoused might be less able to take protective measures during wildfires than people who are housed.

Interviews with people who were unhoused in Salt Lake County (UT, USA) revealed that 61% of interviewees reported physical reactions, 37% reported emotional distress, and 89% had sought medical attention due to air-pollution exposure.<sup>22</sup> However, Salt Lake County has unique air-pollution patterns due to its topography and climate that are different from southern California. Anderson and colleagues<sup>16</sup> discussed the importance of assessing the effects of climate change-related events, such as wildfire smoke, on the health of people who are unhoused.<sup>16</sup> Although several studies worldwide mention air pollution and wildfire smoke as risk factors for people who are unhoused, more research is needed to assess the health effects in this vulnerable group and inform interventions and policy measures to protect them while more permanent solutions, such as affordable housing, are implemented to target the causes of this vulnerability.

Clean-air centres are a potentially effective and easily implemented strategy to protect people who are unhoused during wildfires. However, considering and adapting to their specific needs are important. For example, people who are unhoused can be apprehensive about leaving their belongings for fear of theft<sup>41</sup> or might have no transport to these sites. Some cities in California have implemented targeted outreach in collaboration with service providers for people who are unhoused to offer free transportation to clean-air centres and outreach teams that focus on trust-building and meeting people who are unhoused where they are currently located.<sup>41</sup> Including people who can attend to mental health needs in outreach teams could also be important.

There are major structural issues at the neighbourhood and city level in the USA that can increase the number of people who are unhoused, but that are also increasingly harmful to these people. For example, gentrification adversely affects the health of people who are unhoused by decreasing public services and threatening the quality of their health care.<sup>42</sup> A cross-sectional study in Seattle (WA, USA) showed that inadequate shelter

availability and scarce resources are concerns for people who are unhoused during extreme weather.<sup>43</sup> Programmes such as the Inclement Weather Shelter Program in San Diego (CA, USA)<sup>44</sup> provide additional shelter capacity during inclement weather, but are only open in exceptional weather conditions related to cold temperature and rain. These types of programmes could become operational during other forms of extreme events, including wildfires, to ensure that people who are unhoused can access shelter during these events. However, the most effective strategy to increase the resilience of people who are unhoused to wildfire smoke is safe and sustainable housing.<sup>41</sup> Cohesive strategies to increase housing at all income levels, especially for low-income households, and expanding societal supports to prevent extreme poverty and homelessness are crucial for overall population health and as a preventive measure during extreme weather events.<sup>45</sup> Additional research and efforts should be conducted to inform effective policy measures specifically targeted to protect these vulnerable populations in the context of climate change.

Our study had several limitations. First, data were from a single health-care system with two hospitals in San Diego and did not include individuals seen in other hospitals. Second, we used emergency-department visits as an acute outcome, but some emergency-department visits could have been related to pre-existing diagnoses or conditions. Future work should explore differing effects of air pollution on both existing conditions and new diagnoses. Third, we might have misclassified exposures for people who were unhoused as we used one weighted exposure measure from data on one night in January. Fourth, there could be seasonal health-seeking differences in people who were unhoused due to climate and seasonal changes in available shelter and support for this population. For example, the Inclement Weather Shelter Program in San Diego is generally operational from November to March.<sup>44</sup> Finally, there could have been differences between people who were unhoused and who were housed that stopped them from being directly comparable, such as demographic characteristics, exposure misclassification, and health-care-seeking behaviours. Future research should consider how chemical differences related to wildfire smoke could be driving differences in adverse health effects, as well as how the direct effects of wildfires, such as evacuations and mobility changes, might affect people who are unhoused.

People who are unhoused could be susceptible to the harmful effects of wildfire smoke in the USA, more so than air pollution from other sources, highlighting the need to prioritise their specific needs and provide targeted strategies. Evidence from the USA suggests that wildfires will become more frequent and severe due to climate change and will increasingly co-occur with extreme heat and other weather events that also disproportionately affect people who are unhoused.<sup>20,46</sup> Targeted

efforts protecting people from climate stressors can be effective measures to protect those who are unhoused and should be implemented concurrently with long-term efforts to address the causes of homelessness.

#### Contributors

LS conceptualised the study, conducted the formal analysis, visualised the data, and wrote the original draft of the manuscript. AN conducted the literature review, did the formal analysis, visualised the data, wrote the original draft of the manuscript, and reviewed and edited the manuscript. ES conducted the literature review, wrote the original draft of the manuscript, and reviewed and edited the manuscript. EMC conceptualised the study, curated the data, and reviewed and edited the manuscript. JJB curated the data and reviewed and edited the manuscript. TCC curated the data, was a supervisor, and reviewed and edited the manuscript. RA conducted the formal analysis and reviewed and edited the manuscript. AG was a supervisor and reviewed and edited the manuscript. TB conceptualised the study, conducted the formal analysis, was a supervisor, and reviewed and edited the manuscript. LS, EMC, JJB, and TB accessed and verified the data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

#### Declaration of interests

We declare no competing interests.

#### Data sharing

Particulate matter data are available from [https://github.com/benmarhnia-lab/Wildfire\\_PM25\\_California\\_ZIP\\_and\\_census\\_tract](https://github.com/benmarhnia-lab/Wildfire_PM25_California_ZIP_and_census_tract). Health data are available from <https://blink.ucsd.edu/technology/help-desk/queries/warehouse/overview.html>.

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