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Environmental justice analysis of wildfire-related $PM_{2.5}$ exposure using low-cost sensors in California

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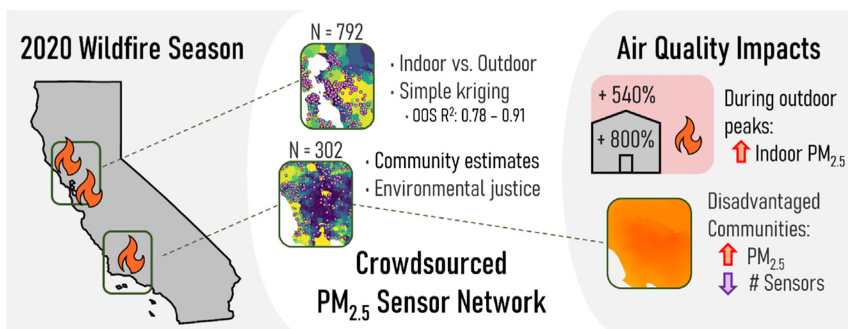
HIGHLIGHTS

- Wildfire may exacerbate health disparities & environmental justice concerns.
- Low-cost $PM_{2.5}$ sensors improve wildfire impact assessment.
- Increases in $PM_{2.5}$ correlate with wildfire activity (within 30 km).
- Indoor increases in $PM_{2.5}$ concentrations mimic outdoor $PM_{2.5}$ increase patterns.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing number and severity of wildfires is negatively impacting air quality for millions of California residents each year. Community exposure to $PM_{2.5}$ in two main population centers (San Francisco Bay area and Los Angeles County area) was assessed using the low-cost PurpleAir sensor network for the record-setting 2020 California wildfire season. Estimated $PM_{2.5}$ concentrations in each study area were compared to census tract-level environmental justice vulnerability indicators, including environmental, health, and demographic data. Higher $PM_{2.5}$ concentrations were positively correlated with poverty, cardiovascular emergency department visits, and housing inequities. Sensors within 30 km of actively burning wildfires showed statistically significant increases in indoor (~800 %) and outdoor (~540 %) $PM_{2.5}$ during the fires. Results indicate that wildfire emissions may exacerbate existing health disparities as well as the burden of pollution in disadvantaged communities, suggesting a need to improve monitoring and adaptive capacity among vulnerable populations.

1. Introduction

Millions of wildland acres are consumed every year in the Western United States by wildfires, which are exacerbated by global climate change effects such as extended periods of drought and elevated surface temperatures (Dennison et al., 2006, Westerling et al., 2006, Goss et al., 2020). Decades of fire suppression in the western US have also increased fuel load for fires, which when combined with changing climates further exacerbate fire risk (Marlon et al., 2012).These wildfires cause increasing economic and public health burdens (Kochi et al., 2012, Liu et al., 2015, Smith, 2020). Wildfires emit both gas phase chemicals and particulate matter (PM) into the atmosphere where local, regional, and long-range air quality impairments have been reported (Primbs et al., 2008, Sekimoto et al., 2018, Kang et al., 2014, Greenberg et al., 2006). The resulting impact of wildfire-associated fine PM ($PM_{2.5}$, aerodynamic diameters smaller than or equal to 2.5 μm) on the planet – in terms of the Earth's

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energy balance and the health of human populations – is a global environmental and public health concern (Burke et al., 2021), particularly since exposure to $PM_{2.5}$ has been linked to a wide variety of acute and chronic adverse health impacts (Xing et al., 2016, Williamson et al., 2016, Klepeis et al., 2001, Sharma et al., 2020).

Community exposure to wildfire associated $PM_{2.5}$ can occur in both outdoor and indoor environments. Outdoor $PM_{2.5}$ contributes to indoor $PM_{2.5}$ concentrations through infiltration, and as a result, emissions of $PM_{2.5}$ from wildfires have been shown to degrade indoor air quality as well as outdoor air quality (Liang et al., 2021, Shrestha et al., 2019). In the United States, people spend 80–90 % of their time indoors (Dennison et al., 2006), which elevates the importance of characterizing indoor air quality during wildfire events, particularly because public health advisories during periods of elevated outdoor $PM_{2.5}$ concentrations encourage limiting time outdoors even further (Black et al., 2017, Luo et al., 2019).

Another important consideration with respect to community-level impacts from wildfires is the analysis of spatial trends in exposures, including disproportionate impacts on various population groups. Currently, evidence on the equity implications of wildfire exposures is mixed. A number of recent studies have shown unequal burdens of wildfire emissions on communities of colour and socioeconomically disadvantaged communities (Davies et al., 2018, Masri et al., 2021), while others have found no variation in smoke exposure by socioeconomic status (Gaither et al., 2015) or disproportionate exposures for white, affluent populations (Bi et al., 2020). Characterizing community-level $PM_{2.5}$ exposure and vulnerability during wildfire periods is critical to understanding the full extent of wildfire impacts (Davies et al., 2018, Gaither et al., 2015). All of these potential and established inequities highlight the importance of characterizing the populations most vulnerable to wildfires, particularly within the context of the growing list of adverse chronic and acute health effects associated with wildfire associated $PM_{2.5}$. There is well-established evidence of the impacts of wildfire smoke exposure on respiratory morbidity, such as exacerbations of asthma and chronic obstructive pulmonary disease (Liu et al., 2015; Lassman et al., 2017; Evans et al., 2021), including differential impacts among low-income populations (Jerrett et al., 2005). Recent studies have also quantified the relationship between short-term exposure to wildfire smoke and mortality (Bailey and Gatrell, 1995) and estimated health burdens resulting from wildfire events by applying $PM_{2.5}$ dose-response functions to calculate attributable premature deaths (Zhang et al., 2021). The latter studies have found that exposure to $PM_{2.5}$ due to wildfires has substantial impacts on mortality and resulting economic burdens. A short-term analysis examining specific wildfire events in the fall of 2020 in Washington state found that each week of increased $PM_{2.5}$ exposure from smoke was associated with almost 90 premature deaths in the region (Zhang et al., 2021).

In recent years, the use of low-cost air sensors has allowed for greater spatial resolution of $PM_{2.5}$ measurements (Bi et al., 2020, Feenstra et al., 2019, Malings et al., 2020, Snyder et al., 2013). A number of low-cost sensor networks are now online with publicly accessible data, such as the PurpleAir network used for this study (Feenstra et al., 2019, Magi et al., 2020). The PurpleAir sensor network is currently being reviewed by the US Environmental Protection Agency (EPA) for its reliability to complement EPA's existing regulated air quality monitoring methods (Federal Equivalent Method and Federal Reference Method) (Holder et al., 2020). The addition of the PurpleAir sensor network to the existing EPA national air monitoring network not only increases spatial resolution, but also enables community-specific air quality assessment (Bi et al., 2020, Holder et al., 2020, Kelp et al., 2022).

Prior studies have used low-cost sensors as a tool to investigate disparities in air quality at a community level, demonstrating the value of dense sensor networks (Tanzer et al., 2019). The distribution of commercial low-cost sensors is primarily driven by consumer demand for personal air quality information, not by controlled scientific interest. However, while affordable compared to state-of-the-art scientific instruments, commercially available low-cost sensors still cost hundreds of dollars, which presents a potential barrier to lower-income individuals, families, and communities. This issue leads to a gap in available scientific data, despite growing popularity among both consumers and regulatory agencies.

Several studies have used the PurpleAir sensor network to measure wildfire emissions (Liang et al., 2021, Aguilera et al., 2021), however, the use of this sensor network has not yet been evaluated in the context of community exposure to $PM_{2.5}$ during regional wildfire events. This study aims to use the PurpleAir sensor network to evaluate both indoor and outdoor $PM_{2.5}$ concentrations during California wildfires in 2020 and characterize associated public health and equity implications. We identified PurpleAir sensors that were online and recording data near two population centers – the San Francisco Bay area (SFB), and the Los Angeles County area (LA), encompassing a total population of 20 million people – in proximity to several of the largest wildfires during California's 2020 wildfire season. To perform the exposure analysis, we located indoor and outdoor sensors within a 30 km radius of actively burning wildfires and evaluated the impact of elevated outdoor $PM_{2.5}$ on indoor air quality. We used ordinary kriging to interpolate $PM_{2.5}$ across the PurpleAir network, generating estimates over the wildfire periods for census tracts in our study areas. We then utilized census tract-level environmental justice vulnerability data from the California Office of Environmental Health Hazard Assessment's (OEHHA) CalEnviroScreen 4.0 tool to quantify the correlations between wildfire $PM_{2.5}$ concentrations and several sociodemographic and environmental metrics (August et al., 2021). CalEnviroScreen integrates environmental, economic, and health data to generate a score that can be used to identify cumulative environmental burdens and vulnerability for each census tract. The overall CalEnviroScreen score is the product of pollution burden and population characteristics and ranges from 0 to 100, with 0 being the least vulnerable and 100 the most. Per California Senate Bill 535, communities above the 75th score percentile are designated as a “disadvantaged community,” eligible for state adaptation funds (OEHHA, 2022). Overall, this study fills an existing knowledge gap by demonstrating the utility of the sensor network in characterizing community exposure to $PM_{2.5}$ during active wildfires and presenting associated equity implications.

2. Methods

2.1. Identification of CA wildfires

The California fire season of 2020 was the most destructive season on record, with >4.3 million acres burned (Spiller et al., 2021). In 2020 alone, ten wildfires burned over 100,000 acres (Table S1 and Fig. S1). These wildfires were those considered in this study. A search of the PurpleAir network revealed sensors within 30 km of these ten fire perimeters. To perform the exposure analysis, we located indoor and outdoor sensors within a 30 km radius of actively burning wildfire perimeters and evaluated the impact of elevated outdoor $PM_{2.5}$ on indoor air quality. The 30 km radius was chosen as it adequately covered the major population centers and avoided excluding clusters of PurpleAir sensors. Three of these fires, the LNU Lightning Complex, SCU Lightning Complex (Del Puerto fire), and Bobcat fires, had indoor and outdoor sensors within the same communities active for a period of 30 days before the fires broke out through 30 days after full containment of each fire (as declared by the agencies in charge of fire response). Indoor sensors found online during the same periods before, during, and after the fires were paired to outdoor sensors within 10 km for comparison.

This study focused on two major metropolitan areas in California: SFB is a 40,384 km^2 area that includes the San Francisco, Santa Rosa, Sacramento, and San Jose; and LA is a 13,000 km^2 area covering Los Angeles County and parts of Ventura and Orange Counties (Fig. 1). These areas were selected due to the presence of large wildfires (>100,000 acres), large population (>1 million), and a high number of PurpleAir sensors (>100). For the purposes of this analysis, SFB included 2127 census tracts and a population of 9.6 million people, while LA included 2874 census tracts and a population of 12.1 million people.

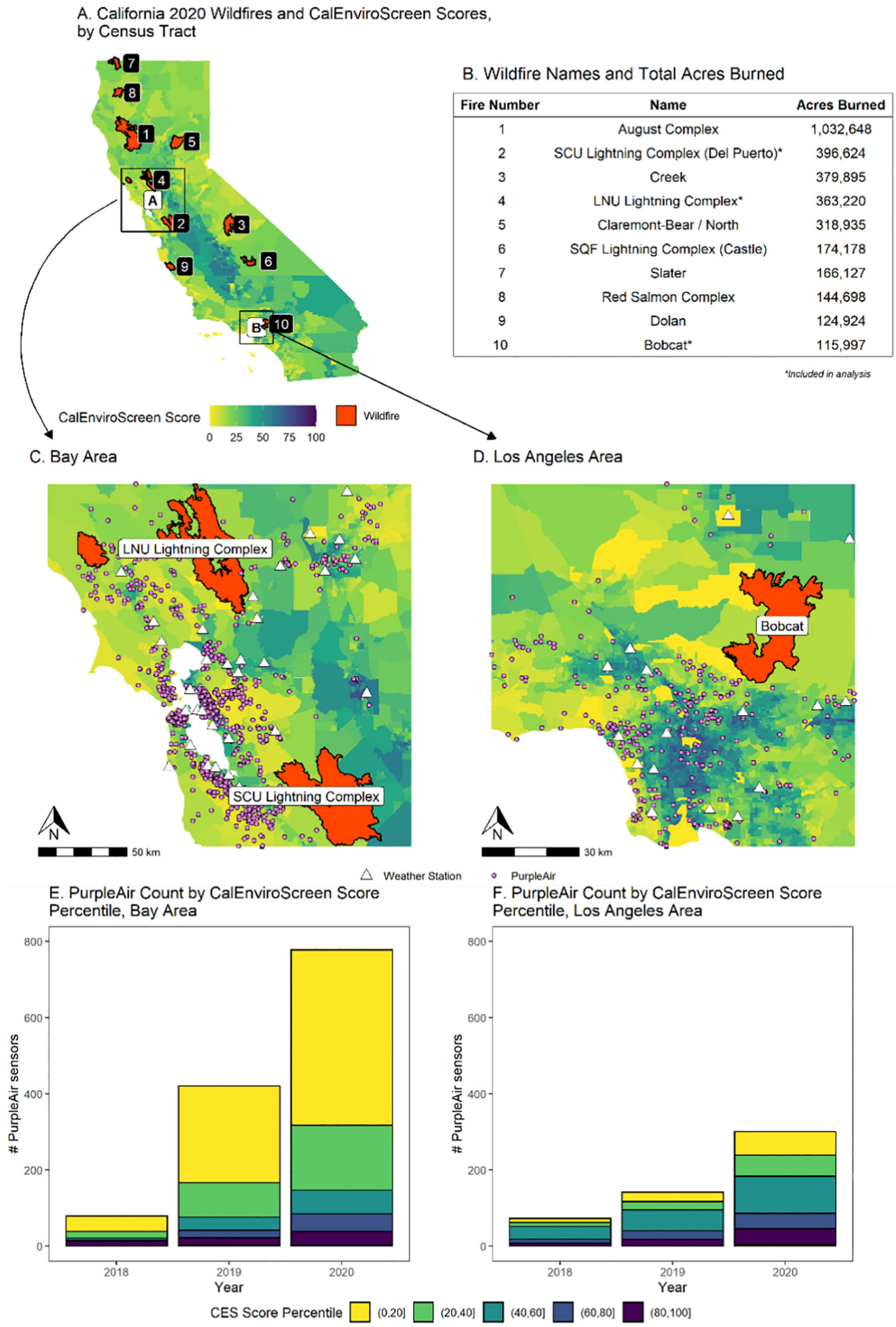

Fig. 1. Maps of fires, study areas, and sensor locations. (A) Location of wildfires >100,000 acres in California (area of fires in orange). Census tracts are colored according the CalEnviroScreen score. (B) Table listing names of each fire alongside the total number of acres burned with numbers corresponding to map locations. Maps of San Francisco Bay Area (C) and Los Angeles Area (D), where study was focused showing PurpleAir sensors (purple dots), weather stations (white triangles), and wildfires within the area. Panels E and F show the number of PurpleAir sensors in each study area, binned by CalEnviroScreen score percentile.

2.2. PurpleAir sensor data quality

2.2.1. Quality assurance/quality control (QA/QC) processes

Hourly average data from both the A and B channels of PurpleAir sensors located within 30 km of each fire were downloaded for a period from 30 days prior to the start of each fire through a period of 30 days beyond the containment of the fire. $PM_{2.5}$ data between channel A and channel B were compared for quality assurance per PurpleAir QA/QC guidelines previously detailed in Connolly et al. (2022). PurpleAir guidelines indicate that the difference between the two channel measurements should not be greater than ± 10 μg/m^3 (for measurements <100 μg/m^3) or greater than ± 10 % of the measurement (for measurements >100 μg/m^3). For measurements found outside those guidelines, the data points were disqualified for analysis. Sensors with >25 % of the total data failing to pass QA/QC were removed from further analysis. After completing the above QA/QC steps, the average $PM_{2.5}$ measurements of channels A and B were calibrated using the following wildfire correction equation from the US EPA, which calibrates PurpleAir data against federal reference methods (Holder et al., 2020).

Sensors that may have potentially been mislabeled in terms of indoor vs outdoor locations were evaluated by plotting temperature against date. Outdoor sensors are expected to have normal daily temperature and relative humidity fluctuations; sensors with <10 °F of temperature fluctuation within one day the study period were suspected to have been installed indoors and were subsequently disqualified from analysis. Likewise, indoor sensors fluctuations in temperature and relative humidity were compared to nearby outdoor sensors (Liu et al., 2022). Only one indoor sensor was found to have statistically non-different data with the nearest outdoor sensor, which was considered to either be placed outdoors or near an open window and was thus disqualified from analysis. Lastly, any observations that corresponded to temperatures outside the PurpleAir acceptable range of -40 °F < Temperature < 200 °F (-40–93C°) and/or 0 % < relative humidity (RH) < 100 % were removed.

After completing the above QA/QC steps, the average $PM_{2.5}$ measurements of channels A and B were calibrated using the following correction equation from the US EPA (Evans et al., 2021):

$$PM_{2.5} = \begin{cases} 0.52 * PA_{cf1} - 0.086 * RH + 5.75 & \text{if } PA_{cf1} \leq 343\ \mu g/m^3 \\ 0.46 * PA_{cf1} + 3.93 * 10^{-4} * PA_{cf1}^2 + 2.97 & \text{if } PA_{cf1} > 343\ \mu g/m^3 \end{cases} \quad (1)$$

where PA_{cf1} denotes the PurpleAir higher correction factor data averaged from the A and B channels and RH is in percentage units. The final dataset in the spatial analysis included 792 PurpleAir (12 indoor) sensors in SFB and 297 (3 indoor) sensors in LA.

2.2.2. Wildfire timeframes

Wildfires vary in their size, duration, and location, and they all have different periods of activity throughout their timelines. To differentiate between different phases of activity for each wildfire, we define the period when the fire is actively expanding its perimeter (or footprint) as the Early-fire period for this study. The period of time between ~70 % containment – which corresponds with little to no expansion of the perimeter – and full containment is defined here as the Late-fire period. Data from 30 days before fires broke out are defined as Pre-fire, and data during the 30-day period after full containment of the fires (as reported by the fire-fighting agencies for each fire) are defined as Post-fire. Dates for each of the fires considered for this project can be found on Table S1.

2.2.3. Statistical analysis

The mean indoor and outdoor $PM_{2.5}$ measurements and indoor/outdoor (I/O) ratios for each of the fire periods were compared through one-way ANOVA on Ranks, with the Dunn's method for pairwise comparisons applied due to the non-normal distribution of the data (Wigtil et al., 2016). When comparing $PM_{2.5}$ measurements to variables in the CalEnviroScreen dataset, the Pearson correlation coefficient (p_{corr}) and associated p-values were calculated. Statistical significance for all statistical tests was established as p-value ≤ 0.05.

2.3. $PM_{2.5}$ exposure modeling

At the time of study, sensor coverage in both SFB and LA was incomplete (Fig. S2). Therefore, in order to generate $PM_{2.5}$ estimates for all census tracts in both study areas, a previously established approach was used to interpolate $PM_{2.5}$ estimates using ordinary kriging (Ravazzani et al., 2020, Cascio, 2018). The geometric mean $PM_{2.5}$ was calculated and used to derive analytical semivariograms for the PurpleAir network with a combination of automatic fitting and manual adjustments to individual parameters (Fig. 2). The semivariogram quantifies and models the degree of spatial autocorrelation in a spatial dataset. In this study, we consider the spatial autocorrelation between PM2.5 measurements in the PurpleAir data. Under the assumption that the theoretical semivariogram for $PM_{2.5}$ remained constant within each time period, hourly estimates of $PM_{2.5}$ for each census tract polygon were generated using block kriging (Reid et al., 2016). Two algorithms were evaluated: (1) standard ordinary kriging, and (2) the Win-OK algorithm, which restricts interpolator sensors to those upwind of the point of interest (Doubleday et al., 2020). These two algorithms were compared using leave-one-out cross-validation. Meteorological data were downloaded using the worldmet package in R, which sources from weather stations managed by the National Oceanic and Atmospheric Administration (Liu et al., 2020). Hourly wind directions were interpolated from weather stations in the study area using inverse distance weighting (Matz et al., 2020). In order to reduce uncertainty during model validation, standard ordinary kriging was also validated with 10-fold cross validation.

Table S2 and Fig. S3 summarize the results of 10-fold cross validation in the PurpleAir dataset. We found excellent agreement between predicted and observed results, with mean out-of-sample (OOS) cross validation R^2 values ranging from 0.78 to 0.91 depending on the study area and timeframe. Higher R^2 statistics corresponded to denser networks of sensors and sensors with low R^2 values in both study areas were found in areas with less sensor coverage. Regardless of the timeframe, a small but statistically significant difference was observed in the OOS R^2 (SFB: 0.82, LA: 0.77, p - value <0.05). Root mean squared error (RMSE) values ranged from 1.21 to 7.24. RMSE values normalized to geometric means ranged from 0.27 to 0.33 in SFB and from 0.23 to 0.28 in LA. The OOS cross validation R^2 values during Early- and Late-fire periods exceeded those reported by other fire-specific studies, whereas RMSE values were comparable to existing literature (Table S2), showing strong model performance (Wang et al., 2021). Normalization of RMSE over geometric mean $PM_{2.5}$ resulted in error levels consistent within each region, as well as with other studies assessing PurpleAir sensors (Holder et al., 2020). During Post-fire periods with no large active fires, OOS cross validation R^2 values were greater than those reported by studies investigating ground-level measurements using traditional instruments, and were comparable to other studies analyzing the PurpleAir network in California (Wang et al., 2021, Kirk et al., 2018).

2.4. Environmental justice vulnerability assessment

To investigate the relationship between spatial environmental justice vulnerability and $PM_{2.5}$ concentrations before, during, and after wildfires, modeled $PM_{2.5}$ data were compared to indicators used in OEHHA's CalEnviroScreen 4.0 tool (see the CalEnviroScreen report for detailed methodology) (OEHHA, 2022). CalEnviroScreen is a mapping tool used to assess cumulative environmental impacts and population vulnerability in California communities at the census tract level; version 4.0 contains data from 2015 to 2019 (OEHHA, 2022). The overall score, which ranges from 0 to 100, is the product of two indices: a pollution burden index and a population characteristics index, generated by regularly updated data on 21 indicators. A higher score corresponds to greater environmental justice vulnerability. To evaluate the relationship between modeled $PM_{2.5}$ and variables within the CalEnviroScreen dataset, modeled $PM_{2.5}$ estimates were correlated with CalEnviroScreen percentile-based variables that pertain to environmental pollution (annual $PM_{2.5}$, ozone, diesel $PM_{2.5}$, pesticide levels, toxic releases, road traffic, drinking water contamination, lead risk, cleanup, groundwater threats, hazardous waste, impure water bodies, and solid waste), health (emergency department (ED) visits for asthma and cardiovascular disease (CVD), and low birth weight) and social factors (education attainment, linguistic isolation, poverty, unemployment, and housing burden). Though not included in score calculations, the CalEnviroScreen dataset also includes demographic variables sourced from the US census relating to age (percentages of population under 10, between 10 and 64, and over 65), as well as race and ethnicity (percentages of population classified as Hispanic, White, African American, Asian American, Pacific Islander, and Other/Multiracial).

3. Results

3.1. $PM_{2.5}$ measurements

Fig. 1 summarizes the spatial characteristics of the study areas including the distribution of PurpleAir sensors, location of wildfires, and CalEnviroScreen score percentiles for the two study areas (Fig. 1a and

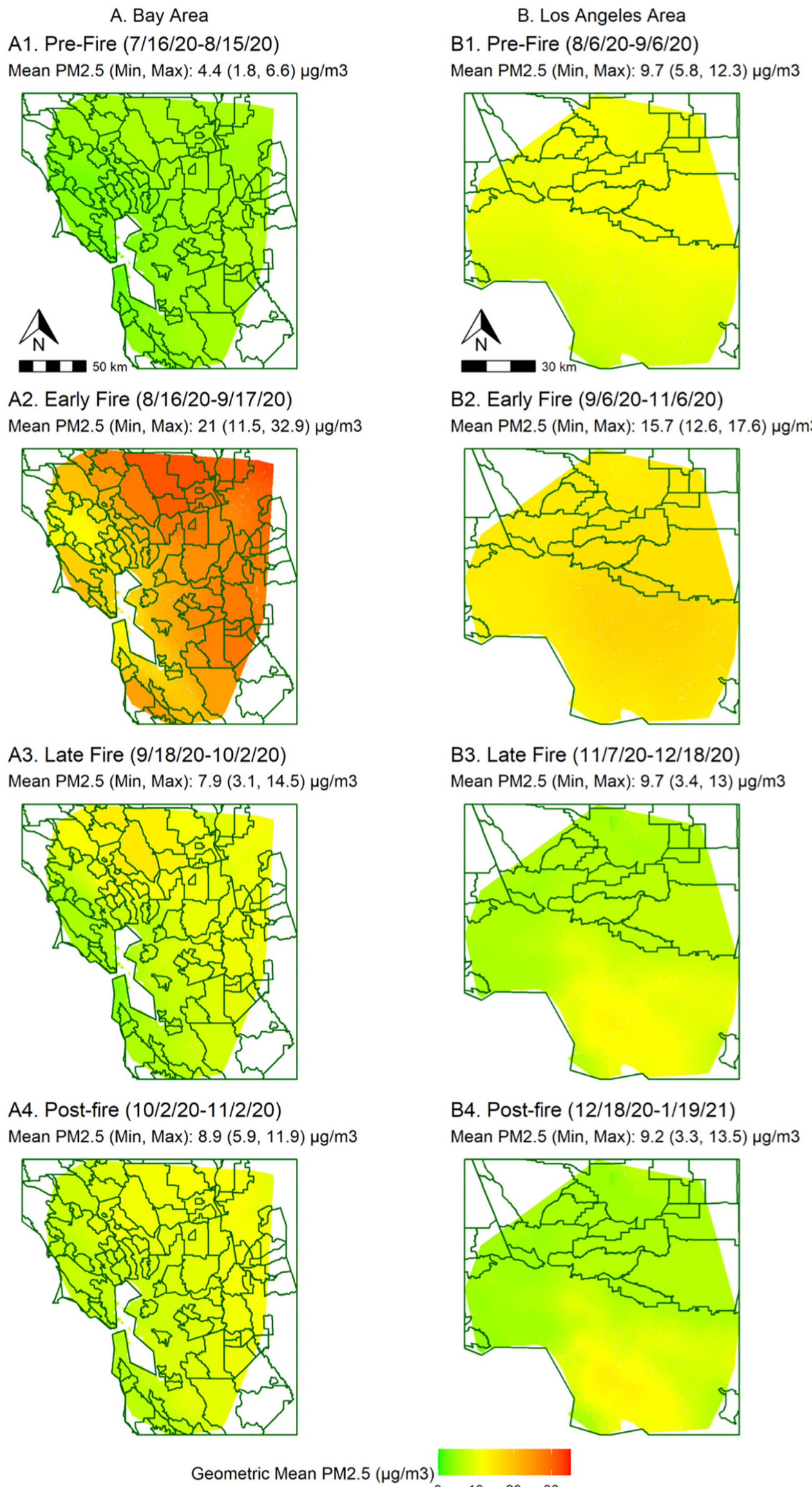

Fig. 2. Spatial distribution of mean $PM_{2.5}$ concentrations in the study areas. Geometric mean $PM_{2.5}$ and summary statistics of each area in each period in SFB area (A1-A4) and LA area (B1-B4). Census tracts with areas >100 km^2 are outlined in dark green. The filled in area represents the area with modeled exposure, defined by the convex hull of the PurpleAir network.

b). Fig. 1c and d illustrate the distribution of PurpleAir sensors by CalEnviroScreen score percentile. A total of 782 sensors with usable data were identified in the SFB area during two major wildfires, the SCU and LNU complex fires that impacted the area from August 16th through October 2nd, 2020 (Table S1, Fig. S1). Census tracts in the lowest 25th score percentile, which indicate lower vulnerability to environmental health impacts, represent 55 % of all census tracts in the SFB study area and contain 81 % of the PurpleAir sensors. Disadvantaged communities represent 10 % of all census tracts in the SFB study area and contained only 5 % of all sensors. The LA area had 302 sensors with usable data during one major wildfire, the Bobcat Fire, which was active in the area from September 6th through December 18th, 2020. Disadvantaged communities represented 41 % of all census tracts in the LA study area and contained 19 % of all sensors. In both study areas, disadvantaged communities had lower levels of sensor coverage, and were consequently subject to higher levels of uncertainty in the census-tract level modeled $PM_{2.5}$ estimates. This observation is consistent with recent findings that concentration-response functions between $PM_{2.5}$ exposure and mortality, which are currently used by US EPA to estimate benefits of air pollution policies, do not sufficiently represent the health effects of air pollution on disadvantaged communities (Connolly et al., 2022).

For comparative analysis, $PM_{2.5}$ measurements of Pre-fire, Early-fire, Late-fire, and Post-fire periods were statistically compared. Arithmetic mean (referred to simply as mean hereinafter) and geometric mean concentrations (both presented due to skewed $PM_{2.5}$ concentrations during wildfire events), as well as standard deviations (SD) and interquartile ranges (IQR) across the SFB and LA study areas during the four established time periods are summarized in Table 1. Across time periods in the SFB area, the $PM_{2.5}$ geometric mean increased fivefold from 4 μg/m^3 to 20 μg/m^3 between Pre-fire and Early-fire periods. During the Late-fire period, it decreased to 8 μg/m^3. The Post-fire $PM_{2.5}$ geometric mean in the SFB area was 9 μg/m^3. In the LA area, between the Pre-fire period and Early-fire period, the $PM_{2.5}$ geometric mean increased from 10 μg/m^3 to 16 μg/m^3. During the Late- and Post-fire periods, it was 10 μg/m^3 and 9 μg/m^3, respectively. It is hypothesized that these decreases may be due to a combination of reduction in size of the fires and of a gradual change from a flaming to a smoldering fire regime. However, due to a lack of data, this hypothesis cannot be tested in the present study.

Fig. 2 presents modeled spatial variations of $PM_{2.5}$ during the four fire periods, which demonstrates how different communities in the same region can experience differential impacts from regional wildfires. During the Early-fire period in the SFB area when $PM_{2.5}$ peaked, the geometric mean concentrations ranged from 12 μg/m^3 to 33 μg/m^3 in individual census tracts, a nearly three-fold increase between census tracts within 50 km of one another. In the LA area, $PM_{2.5}$ similarly peaked during the Early-fire period, although at lower levels compared to the SFB area. During this period, the $PM_{2.5}$ geometric mean ranged from 13 μg/m^3 to 18 μg/m^3.

Modeled $PM_{2.5}$ estimates were correlated with CalEnviroScreen percentile-based variables that pertain to environmental pollution, health, and social factors. Fig. 3 illustrates the magnitude and significance of the Pearson correlations between estimated $PM_{2.5}$ concentrations and all variables in the CalEnviroScreen dataset in both study areas across the four time periods. In the SFB area, notable findings include statistically significant correlations between $PM_{2.5}$ exposures and CVD ED visits in all four periods, as well as significant correlations between unemployment and $PM_{2.5}$ during the Early-, Late-, and Post-fire periods. Asthma ED visits in the SFB area were positively correlated with $PM_{2.5}$, though only significantly during the Post-fire period.

Environmental justice-related disparities were more pronounced in the LA area, where disadvantaged communities represented 41 % of all census tracts. During the Early- and Late-fire periods, significant positive correlations were observed for several environmental pollution variables, including lead risk and toxic releases. Like in the SFB area, positive correlations were observed between CVD and asthma ED visits and $PM_{2.5}$, though both correlations were only significant during the Late- and Post-fire periods. Numerous correlations between social factors and $PM_{2.5}$ were observed during multiple time periods in the LA area, including education, linguistic isolation, poverty, unemployment, and housing burden. Fig. 3 also shows that areas exposed to higher levels of $PM_{2.5}$ tended to be non-white, with higher levels of $PM_{2.5}$ negatively correlated with the percentage of non-Hispanic white population. Of the other racial/ethnic groups, Hispanic percent population had the most consistent positive correlations with $PM_{2.5}$ levels in the LA area, followed by African American.

3.2. Influence of outdoor air quality on indoor $PM_{2.5}$

To fully characterize exposures to wildfire smoke, $PM_{2.5}$ concentrations in indoor environments were also examined. Only 15 indoor PurpleAir sensors (12 in the SFB area, and 3 in the LA area) were found with data that passed QA/QC during the study periods. These indoor sensors were matched to nearby (within 10 km) outdoor PurpleAir sensors. Temporal analysis of indoor and outdoor PurpleAir sensor data show that indoor $PM_{2.5}$ mimicked patterns of outdoor $PM_{2.5}$ during the different periods of the wildfires (Fig. 4). Analysis of the data revealed statistically significant increases in the mean of indoor $PM_{2.5}$ concentrations, ∼800 % (Early-fire) and ∼300 % (Late-fire), and outdoor $PM_{2.5}$ concentrations, ∼540 % (Early-fire) and ∼200 % (Late-fire) as compared to Pre-fire concentrations (Fig. 5, Table S3, and Fig. S4). These data align with another wildfire study using PurpleAir sensors which indicate elevated indoor concentrations of $PM_{2.5}$ when people stay indoors (Liang et al., 2021). In the SFB area, both indoor and outdoor $PM_{2.5}$ concentrations remained elevated after full containment of the SCU and LNU fires (Fig. 4a, b, and c), which may reflect the impact from several smaller regional fires still burning in the Northern and Central California areas. In the LA area (Fig. 4d, e, and f), elevated outdoor $PM_{2.5}$ concentrations before the outbreak of the Bobcat fire were possibly the result of smaller wildfires burning in the Southern California area during that time. Analysis of the I/O ratio of mean $PM_{2.5}$ concentrations (Fig. 5c and d) shows differences in indoor $PM_{2.5}$ that could either be due to intrusion from outdoor $PM_{2.5}$ levels, and/or from increased indoor activity. Overall, the small number of available indoor sensors in both study areas (only 15 in total, and only three in the LA area) limits the ability to draw conclusions regarding the cause of the observed elevated increases of indoor $PM_{2.5}$ during the wildfire study periods.

4. Discussion

4.1. Wildfire impacts on $PM_{2.5}$ concentrations

As shown in Fig. 2, the modeled $PM_{2.5}$ variations demonstrate how different communities in the same region can experience differential impacts from regional wildfires. Local topography and microclimates likely influenced $PM_{2.5}$ transport throughout impacted areas. Higher $PM_{2.5}$ concentrations in the SFB area compared to the LA area were likely due to the two large fires in the SFB area, as opposed to the single fire in the LA area. As shown in Fig. 1b, the two wildfires in the SFB area collectively burned

Table 1
Table of fire statistics. Summary statistics of $PM_{2.5}$ concentrations in each study area by fire period, including arithmetic mean and standard deviation (SD), and geometric mean and interquartile ranges (IQRs). The rightmost column describes the percentage of census tracts that have exceeded the EPA 24-h $PM_{2.5}$ exposure standard of 35 μg/m^3 for at least one day during a given period.

Study area	Fire period	Arithmetic mean $PM_{2.5}$ (SD) (μg/m^3)	Geometric mean $PM_{2.5}$ (IQR) (μg/m^3)	Percent of census tracts exceeding 35 μg/m^3 (%)
SFB	Pre-fire (7/16/20–8/15/20)	5 (2)	4 (3)	0
	Early-fire (8/16/20–9/17/20)	29 (25)	20 (25)	100
	Late-fire (9/18/20–10/2/20)	12 (14)	8 (14)	99
	Post-fire (10/2/20–11/2/20)	11 (9)	9 (9)	53
LA	Pre-fire (8/6/20–9/6/20)	11 (5)	10 (6)	3
	Early-fire (9/6/20–11/6/20)	18 (9)	16 (10)	53
	Late-fire (11/7/20–12/18/20)	11 (6)	10 (10)	0
	Post-fire (12/18/20–1/18/21)	11 (8)	9 (9)	12

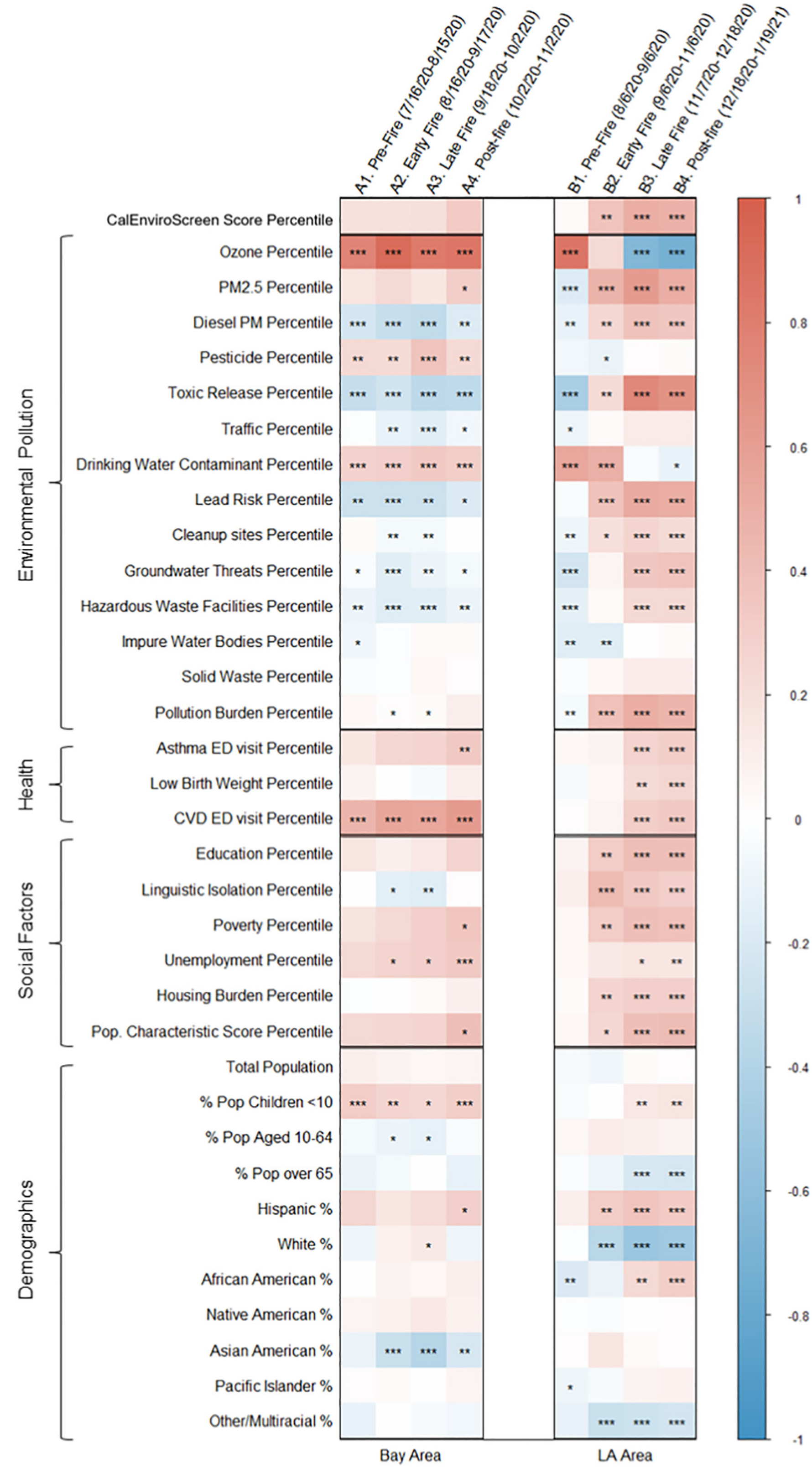

Fig. 3. Correlation matrix between $PM_{2.5}$ concentrations during wildfires and CalEnviroScreen scores. Correlations in the SFB area (left-A panels) and LA area (right-B panels) between mean $PM_{2.5}$ concentrations during different fire periods and social, environmental, and demographic factors in CalEnvironScreen dataset (* = $p_{corr} < 0.05$; **: $p_{corr} < 0.01$; ***: $p_{corr} < 0.001$). Positive correlations are scaled in red, while negative correlations are scaled in blue.

758,844 acres of land over six weeks, compared to the Bobcat fire burning 115,997 acres of land over three months in the LA area (Table S1 and Fig. S1).

The highest $PM_{2.5}$ concentrations were found in both study areas during the Early-fire period compared to other time periods and were statistically significantly higher than during the Pre-fire period (p-value <0.05). The

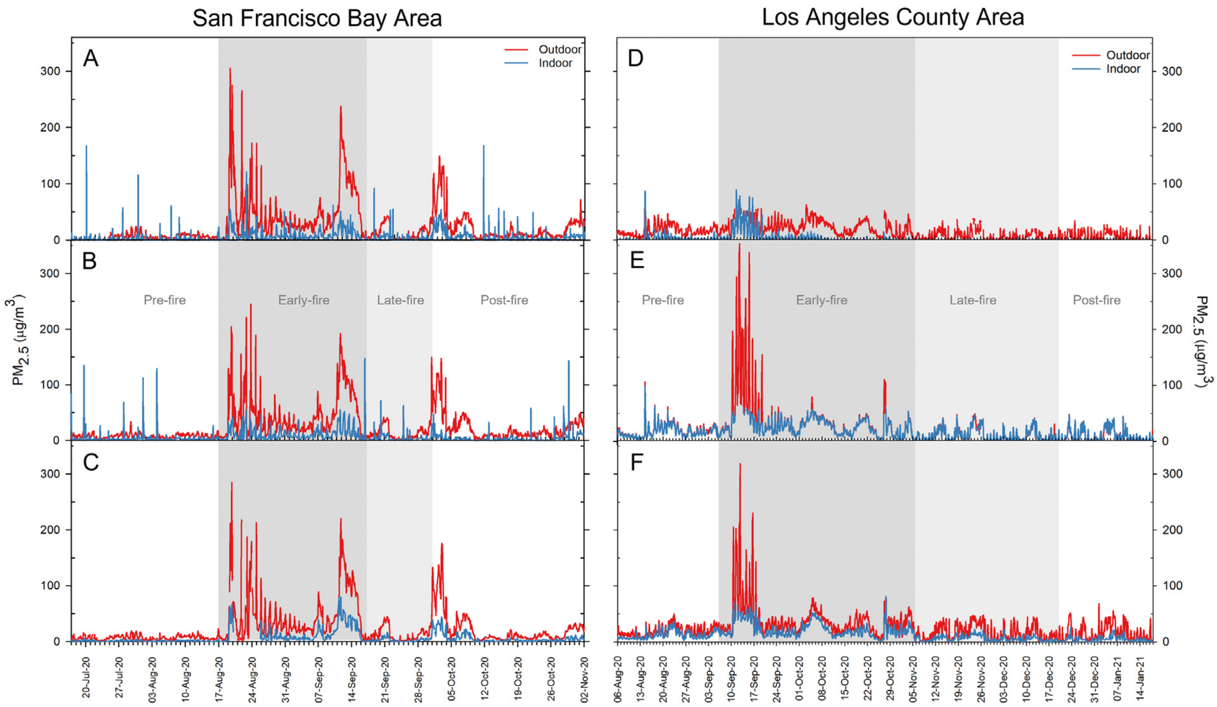

Fig. 4. Time series of $PM_{2.5}$ measurements of indoor (blue) and outdoor (red) PurpleAir sensors for the San Francisco Bay area (4A, 4B and 4C), and the Los Angeles County area (4D, 4E and 4F). The early stage of the active fire period is indicated with a dark grey background, while the late stage of the active fire period is designated with a light grey background. Gaps in data represent time periods with no recorded data, likely due to power outages instituted by power company during fires, or periods with no internet access.

greatest increases occurred in the SFB area during the Early-fire period, when two large wildfires were contributing to $PM_{2.5}$. During the Early-fire period, 100 % of census tracts in the SFB area (with a population of 9.6 million people) were exposed to $PM_{2.5}$ concentrations exceeding the EPA 24-h $PM_{2.5}$ National Ambient Air Quality Standard (NAAQS) of 35 μg/m^3 over at least one 24-h period, compared to 0 % of census tracts in the Pre-fire period. Half of the census tracts in the SFB area (covering a population of 7 million people) exceeded the EPA 24-h standard at least

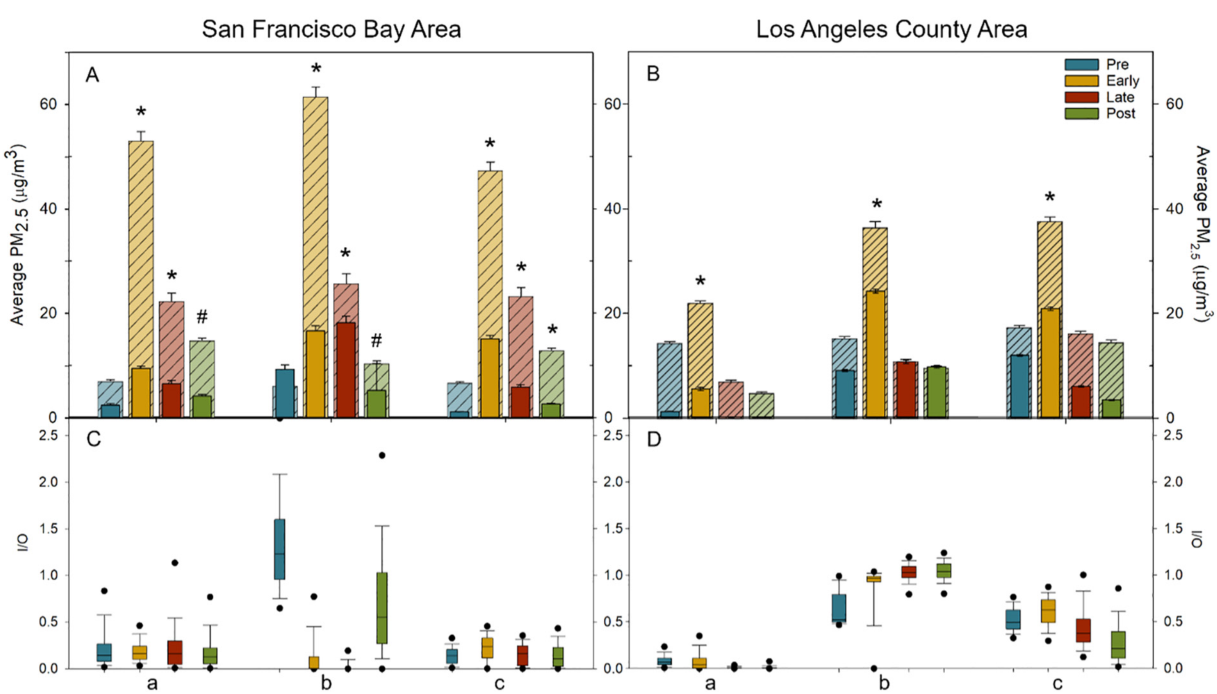

Fig. 5. Plots showing the mean (±1 SE) hourly $PM_{2.5}$ concentration (μg/m^3) for indoor (solid bars) and outdoor (striped bars) sensors for the San Francisco Bay area (5A) and the Los Angeles County are (5B). Statistically significance changes (p-value ≤ 0.05) from the pre-fire period are indicated with (*) for both indoor and outdoor sensors. Outdoor sensor means that are statistically different from pre-fire means are indicated with (#). The indoor/outdoor ratios for sensors in the same community are shown in box plots for the San Francisco Bar area (5C) and Los Angeles area (5D) fires. Boxes represents the interquartile of $PM_{2.5}$ measurements with the median represented by the solid line in the box. Whiskers represent the standard deviation and the 95th percentile shown as dots outside the whiskers.

seven times throughout the wildfires. During the Early-fire period, the PurpleAir network recorded over 84 million person-days of exposure, calculated by multiplying the population exposed by number of days of exposure to $PM_{2.5}$ concentrations above the NAAQS. In the LA area during the Early-fire period, 53 % of census tracts, representing a population of 6.5 million people, exceeded $PM_{2.5}$ NAAQS over at least one 24-h period, compared to 3 % of LA area census tracts in the Pre-fire period. Half of these census tracts (covering 3.2 million people) exceeded the standard three or more times (Table 1), recording 19 million person-days of exposure (Fig. S5). Apart from a small handful of census tracts in the LA area, most census tracts in the area did not exceed the EPA standard prior to the fire (Table 1). After the Early-fire period, both the number of census tracts and the number of days for each census tract exceeding the EPA standard declined, with more pronounced decreases in the LA area. Nevertheless, even one month after wildfire containment, air quality in the SFB area in over half of census tracts continued to exceed EPA standards. It should be noted that PurpleAir sensors are not designed to monitor compliance. Nevertheless, we found that our modeled $PM_{2.5}$ estimates correlated very well with EPA monitors ($r = 0.92$). Since our modeled data underestimate EPA measurements by about 30 %, we can consider our exposure estimates conservative.

The Pre-fire $PM_{2.5}$ levels and spatial distribution in LA were unexpected, given that regional $PM_{2.5}$ levels in California (1) tend to be lower during the summer compared to winter, and (2) tend to exhibit spatial patterns more similar to that of the Post-fire period compared to the Pre-fire period (Fig. 2) (Keeley and Syphard, 2021). Shortly before the Bobcat fire, a smaller fire known as the Apple fire ignited east of the study area, likely affecting background $PM_{2.5}$ levels. To evaluate this hypothesis, the spatial distribution of $PM_{2.5}$ in the PurpleAir network between 2018 and 2019 was compared to the 2020 measurements. Of the three years with adequate PurpleAir data in LA, records show that only 2019 did not have an active wildfire between July 16 and August 15, and the spatial distribution of $PM_{2.5}$ differed between 2019 and the two years with active wildfires, i.e., 2018 and 2020 (Fig. S2). Therefore, $PM_{2.5}$ measurements in LA during the month before the Bobcat fire should not be interpreted as representative of background levels, as these Pre-fire $PM_{2.5}$ measurements likely captured the effect of the Apple fire.

4.2. Considerations for public health and equity

We explored the implications of wildfire $PM_{2.5}$ exposures at the census tract level. Although the correlations between $PM_{2.5}$ concentrations and environmental justice indicators do not characterize the full extent of disparities in air pollution exposures between various population groups during wildfires, this analysis identifies several disparities relating to environmental pollution, health, and sociodemographic characteristics in both study areas during wildfire episodes. Notably, in the LA area, statistically significant positive correlations were observed during the Bobcat wildfire between $PM_{2.5}$ levels and the overall CalEnviroScreen score, indicating that wildfire associated $PM_{2.5}$ exposures were occurring in communities already determined to be vulnerable according to environmental justice indicators (Fig. 3). This observation takes place despite the fact that wildfires in LA, including the Bobcat fire, tend to occur around higher income areas (Matz et al., 2020). Communities affected by environmental justice issues in LA tend to be in denser, more urban parts of the metropolitan areas, often far from the wildland-urban interface. However, the findings reported in this study suggest that increases in $PM_{2.5}$ exposures during wildfires are not isolated to the communities near the fire perimeter.

Although correlations with the overall score were not statistically significant in the SFB area, investigation of the correlations between $PM_{2.5}$ and individual variables revealed striking disparities. Correlations between $PM_{2.5}$ and CVD-related ED visits during the wildfire periods indicated that wildfire smoke had the potential to exacerbate existing cardiovascular vulnerability, considering the established adverse impact of $PM_{2.5}$ exposure on CVD under non-wildfire conditions (Fig. 3) (Evans et al., 2021). In both study areas, strong associations were observed between pollution burdens (such as toxic releases and drinking water contamination) and $PM_{2.5}$ during the wildfire periods, indicating disparities between populations (Fig. 3).

Ultimately, the census tract correlations shown between $PM_{2.5}$ levels and preexisting social, environmental, and health inequities provide evidence that the health burdens in underserved communities have the potential to be worsened by wildfire emissions. Disparities in measures such as English literacy and education attainment underscore the need for simple community-focused messaging and multi-language resources available during wildfire events (Fig. 3). In the LA area, the positive correlations between wildfire $PM_{2.5}$ and housing burden suggest that those affected by poorer air quality during the Bobcat fire face relatively higher housing-related costs, which may result in less adaptive capacity, including the inability to afford (or legal right to install) proper air filtration equipment, HVAC systems, or other measures that would help reduce the impact of air pollution from wildfires (Davies et al., 2018, Matz et al., 2020).

Another recent study estimated the economic valuation of air pollution-related mortality from 2018 California wildfires to be \$32.2 billion for >3500 deaths (Wang et al., 2020). As the PurpleAir sensor network continues to grow, future studies quantifying the wildfire-associated health and economic burdens between population groups can build upon our current assessment of the equity implications of exposures.

4.3. Indoor/outdoor $PM_{2.5}$ relationships during wildfires

The lack of information about building specifications, indoor environmental conditions, and inhabitant activity, due to all data being publicly sourced, reduces the ability to draw firm conclusion about the impact of wildfire related $PM_{2.5}$ on indoor air quality in this study. Previous studies have documented increases in indoor $PM_{2.5}$ levels correlated with time spent indoors, which represents a portion of the data we cannot account for in this study (Klepeis et al., 2001, Liang et al., 2021, Shrestha et al., 2019, Luo et al., 2019). Nevertheless, this study proves the efficacy of the PurpleAir sensors to evaluate indoor $PM_{2.5}$ concentrations during wildfire events. It provides evidence that the scientific community would benefit from an increase in the number of indoor sensors in wildfire prone areas to decrease the uncertainty in the measurements of indoor $PM_{2.5}$ concentrations, and increase researchers' capacity to develop community-specific infiltration factors and draw conclusions about wildfire $PM_{2.5}$ intrusions(Kelp et al., 2022, Lu et al., 2021). It is also important to note that, due to the lack of PurpleAir sensors in disadvantaged communities, existing analyses on infiltration do not have the data needed to investigate disparities in adaptive capacity and wildfire resilience between communities (Davies et al., 2018). Increasing available data could help to better inform public health officials and community leaders as to how to protect residents from wildfires.

4.4. Implications and limitations of present study

While this study shows how the PurpleAir sensor network could contribute to a better understanding of community exposure to wildfire related $PM_{2.5}$, which is needed to protect the communities most at risk of bearing the cost of wildfire emissions, there are a few limitations. The inequitable distribution of sensors and the small number of available indoor sensors limit the inference and generalizability of the results. Namely, the inequitable distribution of sensors in our study areas (shown in Fig. 1 and Fig. S2) results in variable confidence in our modeled air quality estimates, with more uncertain estimates in disadvantaged communities. The correlations of $PM_{2.5}$ concentrations with variables from the CalEnviroScreen dataset are also not precisely temporally aligned, although this issue is expected to have only minor effects on the presented results because the percentile-based variables represent trends. There may be issues with our modeling technique, as wildfire emissions may violate assumptions necessary for kriging, namely stationarity and isometry. However, we found high levels of agreement between predicted and observed results during OOS cross validation, suggesting that modeling was fairly robust, especially in areas with high densities of sensors. We also found high levels of agreement between modeled estimates and EPA monitors. Our results do not suggest that wildfires are the source of disparities in health or environmental quality, nor do they necessarily indicate that wildfires are the sole cause of increased PM concentrations during the study periods. Instead, assuming that environment and health-related variables remain fairly constant across time, our results suggest that existing disparities could be exacerbated during wildfire events. The underlying associations between wildfire emissions and environmental health disparities warrant future study.

5. Conclusions

This study demonstrated the utility of the PurpleAir low-cost sensor network during the California 2020 wildfire season. Even with <20 % of sensors with usable data located in disadvantaged communities, modeled $PM_{2.5}$ concentrations successfully demonstrate census tract-level variation throughout both study regions (Fig. 2). This study demonstrates that, whereas most wildfires occur near more advantaged communities along the wildland-urban interface, the impact of elevated $PM_{2.5}$ levels is not isolated to those communities. Correlations between modeled $PM_{2.5}$ levels during wildfires and several environmental, health, and sociodemographic-related CalEnviroScreen metrics (Fig. 3) suggest that wildfires may exacerbate existing health disparities and environmental justice concerns. Analysis of data from indoor and outdoor PurpleAir sensors within the same communities demonstrates that, during active wildfires, indoor concentrations of $PM_{2.5}$ increase concurrently with outdoor $PM_{2.5}$ (Fig. 4). Analysis shows that some I/O ratios (Fig. 5) remain consistently low, while others increase above one during wildfires, indicating higher indoor concentrations than outdoor. This observation demonstrates the need for more information about indoor population behavior during wildfires, which can be used to establish wildfire $PM_{2.5}$ infiltration rates among various communities. Finally, this study demonstrates the need for investment in both indoor and outdoor sensors in disadvantaged communities, which could support future research, aid in increasing community resiliency, and ultimately protect vulnerable populations during wildfires (Kelp et al., 2022).

CRediT authorship contribution statement

Y.Z., A.K., and J. L. conceived and devised the research. A.K., J.L., and L.L. performed the research. R.C. contributed to equity analysis. M.B. and Y.Z. secured funding. Y.Z. supervised the research. A.K. and J. L. wrote the first draft of the manuscript. Y.Z., R.C., and M.B. contributed to writing and reviewing the manuscript, and to the interpretation of the results.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced or appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.159218.

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