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The Environmental Justice Implications of Wildfire Smoke: Exploring Differential Exposure and Susceptibility of the 2007 San Diego Fire Storm

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The Environmental Justice Implications of Wildfire Smoke: Exploring Differential Exposure and Susceptibility of the 2007 San Diego Fire Storm

A thesis submitted in partial satisfaction of the requirements

for the degree of Master of Science

in

Earth Sciences

by

Elizabeth Duran

Committee in charge:
Professor Tarik Benmarhnia, Chair
Professor Geoffrey Cook
Professor Jane Teranes

2021

The Thesis of Elizabeth Duran is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2021

DEDICATION

To Roy and Nox.
Thank you for always being there when I needed you all the most.
I’d also like to dedicate this to myself.
A reminder that even through the darkest times, I can persevere.

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ABSTRACT OF THE THESIS

The Environmental Justice Implications of Wildfire Smoke: Exploring Differential Exposure and Susceptibility of the 2007 San Diego Fire Storm

by

Elizabeth Duran

Master of Science in Earth Sciences

University of California San Diego, 2021

Professor Tarik Benmarhnia, Chair

Wildfires are predicted to become more severe and frequent with climate change. Wildfire smoke contains toxic pollutants such as particulate matter 2.5 ($PM_{2.5}$), which has adverse effects to human health. Literature suggests that air pollution health impacts are cumulative, and wildfire $PM_{2.5}$ exacerbates pre-existing conditions, potentially contributing to increasing environmental health inequalities. Multiple studies have suggested that communities from low-SES and minority backgrounds are more impacted by air pollution than their counterparts but the role of wildfires' smoke in health inequalities is still unclear. In this study, we assess the environmental implications of wildfires and wildfire $PM_{2.5}$ by investigating two mechanisms through which wildfire smoke may contribute to health inequalities: differential exposure and differential susceptibility. We use the 2007 San Diego wildfire storm as a case study along with twelve of CalEnviroScreen 3.0's environmental justice indicators and run linear aggressions against wildfire $PM_{2.5}$ and respiratory hospitalizations attributable to wildfire $PM_{2.5}$. We also produce maps for wildfire $PM_{2.5}$, excess respiratory hospitalizations, and all twelve indicators for spatial analyses. Overall, we found a null or negative correlation between wildfire $PM_{2.5}$ and environmental indicators suggesting that low SES communities were less exposed to wildfire smoke during this event. However, we found a positive correlation between respiratory hospitalizations and environmental indicators indicating that low SES communities are systematically more impacted. This suggests that wildfire smoke may contribute to exacerbating environmental injustices through a differential susceptibility mechanism. These findings are important in identifying vulnerable populations and helps inform targeted policies during wildfires events.

Introduction

Wildfires in the Western US in the Context of Climate Change

Anthropogenic climate change poses a myriad of threats to society, among them the increasing damage associated with catastrophic wildfires. Due to changes in precipitation and temperature patterns, wildfires have increased in frequency, duration, and severity (Reid et al., 2016). In fact, forest fires in Western United States are five times more frequent on an annual basis than they were 50 years ago (Balmes, 2018). The damages and costs that are associated with wildfires are not contained to the immediate burned areas; instead, due to the wind factor, these natural disasters do not see borders and are a major public health concern even to those who are thousands of miles away. Along with acres of burned land, wildfires produce an array of negative consequences such as loss of buildings and homes, large scale evacuations, injuries and fatalities, and large economic costs. In the years 2017 and 2018 alone, California wildfires generated $50 billion in damages, 150 fatalities and a loss of 25,000 homes (Abatzoglou et al., 2020; Siddiqui N et al. 2014). In recent years, new preemptive energy strategies called Public Safety Power Shutoffs have been implemented to mitigate against "power line fires." While some successes have been observed, PSPSs have caused negative societal and economic impacts. These consequences include closure of schools and businesses, communication system breakdowns (loss of internet and cell phone coverage), spoiled food, temporary loss of wages and more (Abatzoglou et al., 2020). Additionally, wildfire smoke is known to have direct detrimental effects on human health and contributes to the healthcare burden of smoke-impacted areas (Black et al.,2017). Wildfire smoke can contain or serve as a precursor for air pollutants such as carbon dioxide, ozone, carbon monoxide, complex hydrocarbons, particulate matter and many more (Balmes, 2018; Reid et al., 2016; Reid et al., 2016; Urbanski, 2014).

Wildfires, being episodic, have been viewed as acute environmental distresses. With the increase in severity and frequency of wildfires in the past few years, the destruction, and damages that follow are becoming characterized as a chronic public concern. Studies predict that with the expected warming from anthropogenic climate change, wildfire season will increase both spatially and temporally in the Western US (Dennison et al., 2014). Dennison et al. 2014 found that in all eco-regions studied, the total fire area increased at a rate of 355 km^2 per year, while the number of large fires increased at a rate of seven fires per year; these increases coincided with increasing drought severity. Along with warming and changes in precipitation, wind plays an important factor in wildfire duration and burn coverage. In Southern California, offshore wind events, referred to as Santa Ana Winds, have low relative humidity and quickly dry fuels when they occur before the onset of California's winter precipitation season(Guzman-Morales et al., 2019; Williams et al., 2019). Williams et al., 2019 established a non-linear relationship between large fire and dry fuels and stated that the clearest link between California's increased wildfire activity and anthropogenic climate change is warming-driven fuel drying. The Santa Ana Winds are responsible for transporting wildfire smoke from backcountry areas to densely populated coastal populations (Aguilera et al., 2020). Recent studies have suggested that wildfire season might shift from fall to winter coinciding with the seasonal peak of Santa Ana Winds, and therefore, contribute to the concern of the rise in available wildfire fuels. (Guzman-Morales et al, 2019; Williams et al., 2019).

The Role of Santa Ana Winds in the Context of Wildfires

As mentioned above, strong winds, such as the Diablo Winds in Northern California and the Santa Ana Winds (SAW) in Southern California, play a large role in the transportation of wildfire smoke and its constituents. SAW are episodic reversals of westerly winds in Southern

California; they begin in fall, peak during December, and fall off during spring (Aguilera et al., 2021). These winds are responsible for fanning and spreading wildfires burning in the wildland-urban area and transporting wildfire smoke to densely populated coastal areas (Aguilera et al., 2021; Aguilera et al., 2020). The main constituent in wildfire smoke is $PM_{2.5}$. Because of its small and fine size, particulate matter can remain airborne for weeks and can travel hundreds to thousands of kilometers. As a result, SAW transport and disperse wildfire $PM_{2.5}$ far and wide creating a myriad of health impacts along the way.

Particulate Matter in Wildfire Smoke

The principal pollutant of public health concern from wildfire smoke is particulate matter (PM). $PM_{2.5}$ and PM_{10} are defined as inhalable particulates that are less than 2.5 μm and 10 μm, respectively, in aerodynamic diameter (Reid et al., 2016). $PM_{2.5}$ poses a greater threat to public health because it can penetrate deeper into the lungs, reaching the alveoli and entering the bloodstream (Black et al., 2017). Literature suggests that short-term exposure to ambient $PM_{2.5}$ can lead to increased risk of acute respiratory and cardiovascular disease outcomes; exacerbation of asthma, myocardial infarction, stroke, and chronic obstructive pulmonary disease are just a few examples (Balmes, 2018). Wildfire specific smoke also contributes to the health burden. Globally, an estimated 340,000-680,000 deaths per year are attributed to smoke $PM_{2.5}$, and it has been found that air pollution health impacts are cumulative; as a result, wildfire smoke is known to exacerbate pre-existing health conditions (Marlier, Crnosija, Benmarhnia, IN PRESS). For instance, increases in $PM_{2.5}$ caused by wildfires have been associated with increases in asthma and chronic obstructive pulmonary disease emergency department visits (Balmes, 2018; Black et al., 2017; Reid et al., 2016). Other health conditions including respiratory morbidity, cardiovascular disease, mental health and all-cause mortality have also been linked to wildfire smoke (Aguilera et al., 2021; Balmes, 2018; Black et al., 2017; Reid et al., 2016). Some studies have found that health care utilization related to wildfires persists beyond the initial high-exposure period (Hutchinson et al. 2018), demonstrating that wildfires and wildfire smoke have lasting effects on populations near and far.

The U.S. Environmental Protection Agency's (EPA) 24- hour air-quality standard for acute $PM_{2.5}$ exposure is 35 μg per cubic meter (Balmes, 2018, https://www.epa.gov/pm-pollution/particulate-matter-pm-basics); Because of the amount of robust epidemiologic evidence associated with acute exposure of $PM_{2,5}$ and its negative health impacts to the public, the EPA regulates particulate matter anthropogenic emissions to improve air quality (Balmes, 2018; Ford et al., 2018). Although these improvements are predicted to increase with a decrease in anthropogenic emissions, Ford et al. 2018 found that with the increases of wildfires predicted, fire-related $PM_{2,5}$ will offset any improvements gained; Figure 1 demonstrates that two of the studies simulations (RCP4.5 and RCP8.5) projected fire-related $PM_{2.5}$ concentrations to increase from ~25% to over 50% by 2100. As previously mentioned, there is concern that wildfire season may coincide with the peak of Santa Ana Winds. Augilera et al. 2020 suggested that although Santa Ana Winds may lower $PM_{2.5}$ levels in the absence of a wildfire, during a wildfire, a polluting effect is observed; Santa Ana winds help spread WF $PM_{2.5}$ from inland areas down towards the densely populated coastal zones and cause $PM_{2.5}$ concentrations to surpass the 24-hr national standard of $PM_{2.5}$ (35 μg/m3) (Aguilera et al., 2020). Furthemore, recent studies suggest that $PM_{2.5}$ and WF $PM_{2.5}$ show differences in compositional makeup and therefore may not be equal in toxicity at equal doses. In Aguilera et al., 2021, researchers found up to a 10% increase in respiratory hospitalization admissions attribuable to wildfire smoke in comparison to ambient $PM_{2.5}$. They also found that WF $PM_{2.5}$ is up to 10 times more harmful to human health than

$PM_{2.5}$ from other sources. These studies suggest that future wildfires combined with the predicted climate change influences will only continue to worsen and negatively impact human health regardless of predicted air quality improvements. They also highlight the importance of examing the impacts WF $PM_{2.5}$ could have on other lenses in scope, such as enviromental influences, health, and socioeconomic status (SES) factors.

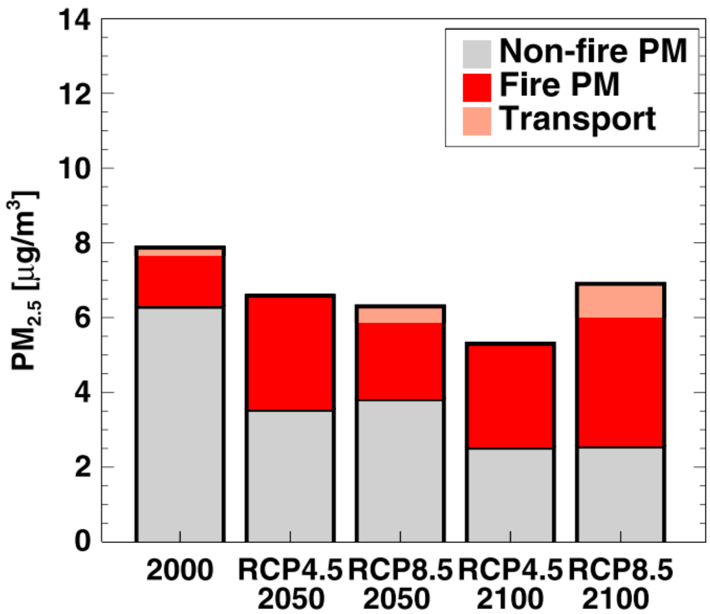


Figure 1: Excerpt from Ford et al., 2018 demonstrating the predicted Fire PM increases in comparison to Non-Fire PM. By 2100, Fire PM will offset any improvements potentially gained by government regulations.

The Environmental Justice Implications of Wildfire Smoke

The destruction and detrimental health effects that are caused by wildfires open up the dialogue and highlight concerns around issues of environmental injustice. The EPA defines environmental justice as “the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies” (https://search.epa.gov/epasearch/?querytext=environmental+justcie&areaname=&areacontacts=&areasearchurl=&typeofsearch=epa&result_template=#/). Environmental justice defines the human relationship with the environment and condemns environmental pollution that can harm ecosystems and communities. It also argues for an equal distribution of resources such as access to transportation, hospitals, green spaces and more. Despite the goal of environmental justice for all, injustice issues do arise. For example, common environmental injustices include food swamps, food deserts and a lack of access to green spaces; food swamps are areas that are filled with high volumes of fast food restaurants while food deserts are residential areas that have limited access to affordable, fresh, and health food options, largely due to a lack of grocery stores (Cooksey-Stowers et al.,2017). Green spaces, such as public parks, gardens, zoos, tree lines and more, have been shown to impact human health by improving air quality, reducing stress, creating greater social cohesion, and enhancing physical activity (WHO, 2016). All three of these environmental injustices are often characteristic of low-income and/or minority neighborhoods (Cooksey-Stowers et al., 2017; WHO, 2016). Several studies have identified exposure to air pollution as an important contributor to environmental injustice (Mohai et al., 2009) and health inequalities. This environmental justice literature has shown how low SES communities or racial/ethnic minority groups were systematically more exposed to higher levels of air pollution from traffic or industrial emissions (Hajat et al., 2015) and also more impacted by such source of exposure (Benmarhnia et al., 2021). These studies highlight the different types of environmental stressors these communities often experience and underscore the importance of achieving environmental equality and equity. However, the specific role of wildfire smoke as a source of exposure has not been explored yet.

As mentioned above, wildfires threaten the health of communities who are already exposed and/or experiencing outside pressures and stressors. These communities may feel the detrimental effects stronger than compared to those who are not. Davies et al., 2018 argued that natural disasters only become disasters due to political, economic, and social variables; variables can consist of language isolation, low SES, race, ethnicity, proximity to hazardous waste and factories, and more (Davies et al., 2018; Paveglio et al., 2018). For instance, language barriers can prevent communities from receiving pertinent information about wildfires such as warnings and evacuations. Researchers found that during the 2007 San Diego wildfire storms, about one-third of the population received no form of communication regarding the wildfire and evacuations; many factors including physical difficulties and language barriers contributed to this lack of communication (Siddiqui N et al., 2014) Another study observed that language barriers prevented Hispanic farm-workers from receiving evacuation notifications, and the only Spanish radio station in the area never received any emergency notifications (Davies et al., 2018). In regard to economics, those with low income may not have enough funds to perform preventative fire measures, such as cutting and trimming bushes and trees and purchasing insurance. They also may lack the resources or social support to modify and come back from a wildfire (Davies et al., 2018) Masri et al.,2021 found that compared to urban census tracts, rural census tracts exhibited higher rates of wildfire burning. Characteristically these rural census tracts had higher rates of vacant homes, poverty, unemployment, low income residents, residents without a college degree and residents without computers/internet (Masri et al., 2021).

SES and environmental factors influence a community's livelihood, and it is important that we recognize that these impacts are not randomly distributed or experienced at the same degree among different communities (Mohai et al., 2015). Language barriers, low income, high rates of air pollution and more can negatively impact the well-being of an individual and adding a natural disaster such as a wildfire to the equation can stir up even more negative consequences and health impacts. The examples shared above demonstrate how crucial it is for policymakers and government agencies to consider environmental justice when distributing resources before, during and after a natural disaster and encourage the continued research of this realm.

Differential Exposure and Differential Susceptibility

Air pollution produces environmental justice issues because people experience the impacts of air quality differently. Due to systematic planning and legislation, communities and individuals may experience health inequities and inequalities. There are two mechanisms for which wildfires can lead to these inequities and contribute to environmental justice issues: differential exposure and differential susceptibility.

With differential exposure, a community systematically experiences higher levels of smoke (WF $PM_{2.5}$) exposure in comparison to their counterparts. Human activities such as settlement patterns, vegetation management, and land use all influence the frequency, severity and pattern of wildfires (Wigtil et al., 2016). Policies and mitigation strategies intended to modify risks and vulnerabilities can vary in effectiveness. For example, homeowners' insurance is typically only affordable to those with higher income or available to those who own rather than those who rent (Davies et al., 2018; Wigtil et al., 2016). Furthermore, human settlement patterns influence exposure to wildfire smoke and air pollution. Because homeowners' insurance helps subsidize the cost of wildfire risk, it incentives human settlement in fire-prone areas which would usually be settlement free (Wigtil et al., 2016). Even more, historic urban planning laws and policies such as housing segregation and redlining encourage disproportionate exposure levels and health inequities (Davies et al., 2018; Lopez-Villafana et al., 2020).

Differential susceptibility occurs when a community may be experiencing the same amount of exposure concentration but suffers worse health impacts and health burden. Susceptibility is related to intrinsic population characteristics such as socioeconomic status or pre-existing health conditions. Literature suggests that wildfire vulnerability is spread unequally throughout communities; people with low SES, pre-existing health conditions such as asthma or cardiovascular disease, housing burden, and/or come from an ethnic/racial minority backgrounds have historically faced harder impacts than communities with high SES, no pre-existing health conditions, or are from the ethnic/racial majority (Davies et al., 2018; Reid et al., 2016; Wigtil et al., 2016). Individuals with a low income background may not have the capability to recover from a disturbance (Davies et al., 2018), and those already dealing with other health conditions (asthma, low birth weight, cardiovascular disease, mental health diseases) may be more susceptible to the negative health impacts and risks that can come from a wildfire (Davies et al., 2018; Rappold et al., 2012; Reid et al., 2016)

It is critical to explore different variables and dimensions that may influence these two mechanisms. Vulnerability can stem from exposure rates, sensitivity, and the ability to cope with wildfire risks and damages. Investigating dimensions that may impact these vulnerabilities would allow us to identify at-risk communities and regions. As a result, examining population and environmental characteristics, such as SES, air pollution, health quality, education and more is crucial in assessing if differential exposure and/or differential susceptibility are contributing to environmental justice issues.

Case Study: 2007 San Diego Wildfire Storm

We decided to perform our analysis with the 2007 San Diego wildfire storm. The large size of the wildfire storm and degree of damages inflicted allows this case study to be highly documented and to provide easy-accessible data. Between October 20 -23 2007, Southern California experienced a large firestorm event that consisted of more than two dozen major fires burning at once (Aguilera et al., 2020). In total, the 2007 wildfires destroyed approximately 3,200 structures and damaged 257 structures, causing 7 civilian fatalities and 161 injuries (mostly among firefighters) (Kochi et al., 2016). 83% of the property damages inflicted were concentrated in San Diego county followed by 14% in San Bernardino Country (Kochi et al., 2016).

Along with over 972,000 acres of burned land, the wildfires inflicted $3.4 million in health care costs for emergency department and hospital visits alone (Kochi et al.,2016). In the San Diego region, Thelen et al., 2013 examined ED visits and found that these visits were nonlinear; the odds of a person seeking care were increased by 50% during peak fire PM concentrations in comparison to non-fire conditions. Furthermore, respiratory diagnoses, especially asthma, were elevated among vulnerable populations, including low-income individuals and young children.

Motivation

Wildfires are projected to become more frequent and severe in time with climate change. There has been extensive research demonstrating a potential increase in environmental, economic and/or health burden as a consequence of these wildfires and smoke. These negative impacts can have environmental justice implications, and wildfires can contribute to environmental injustice by high levels of smoke exposure (differential exposure) or by impacting more communities with low SES variables (differential susceptibility). As a result, it is important to assess which mechanism(s) are being seen. It is also important to examine and determine areas that can modify and mitigate risk at the community level. Furthermore, identifying at-risk communities/vulnerable populations will allow policymakers to know how and who to distribute resources to before, during, and after a wildfire in order to reduce health disparities and health burden.

Objectives

For this study, we wanted to evaluate if this wildfire storm could be characterized as an environmental injustice example. To understand this, we used the following questions to guide our research and assess our results:

1. Is there evidence of differential exposure to WF $PM_{2.5}$?
2. Is there evidence of differential susceptivity with WF $PM_{2.5}$ and respiratory hospitalizations?
3. If either of the two above exists, is the differential exposure and differential susceptibility the same and is it necessary to consider both?
4. Is there a health burden?
    a. If the above is true, can this health burden(s) be explained through environmental justice implications?

For our hypothesis, we predict that communities who are already experiencing other outside sources of stress, such as low-income, linguistic isolation, air pollution etc., will have higher sensitivity to WF $PM_{2.5}$ concentrations and have higher rates of respiratory hospitalizations attributable to WF $PM_{2.5}$, suggesting evidence of environmental injustice.

Methods

Wildfire $PM_{2.5}$ & Respiratory Hospitalization Data

Our study area included 106 ZIP code polygons in San Diego County. The data analyzed covered $PM_{2.5}$ and WF PM $_{2.5}$ concentrations (μg per m^3) and respiratory hospitalizations occurring between October 21^{st} through October 28^{th}, 2007. Using fire perimeters obtained from the Fire and Resource Assessment Program (http://frap.fire.ca.gov/) of the California Department of Forestry and Fire Protection and smoke plume satellite imagery derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Rapid Response System (https://modis.gsfc.nasa.gov/) and the NOAA Hazard Mapping System (https://satepsanone.nesdis.noaa.gov/pub/volcano/FIRE/HMS_ARCHIVE/), our team was able to determine which ZIP codes and days were exposed to wildfire smoke during the 2007 firestorm. Each ZIP code was assigned a daily concentration level for both $PM_{2.5}$ and WF $PM_{2.5}$ over the 8 days of study.

Hospitalization data was derived from the Office of Statewide Health Planning and Development database of patient discharges using daily clinical data. Respiratory hospitalizations include pulmonary diseases such as chronic obstructive pulmonary disease, asthma, pneumonia, and interstitial lung diease-9 (Aguilera et al., 2020).

This data was formatted and distributed through Microsoft Excel spreadsheets. More in-depth details regarding the particulate matter and hospitalization data collection are described in Aguilera et al., 2020 and Aguilera et al., 2021.

CalEnviroScreen 3.0 Data

The California Communities Environmental Health Screening Tool version 3.0 (CalEnviroScreen 3.0, https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30) is an open access online tool created by the State of California Environmental Protection Agency's (CalEPA) Office of Environmental Health Hazard Assessment (OEHHA) to help identify California communities that face a disproportionate burden of pollution and socioeconomic disadvantage (Greenfield et al. 2017, Oehha.ca.gov). It describes the hazard spatial patterns felt in vulnerable communities and acts as a guide for state resource allocations (Greenfield et al. 2017, Cushings et al. 2015). CalEnviroScreen is an environmental justice screening tool made from 20 indicators related to pollution burden, characterized by both exposure and environmental effects, and population characteristics, which consists of sensitive populations and socioeconomic factors. CalEnviroScreen 3.0 multiplies the calculated Pollution Burden by the Population Characteristics of each census tract to generate a CalEnviroScreen Score between 0 and 100. Figure 2 visually demonstrates how CalEnviroScreen produces its score.

The raw data and calculated percentiles for individual indicators and overall CalEnviroScreen Scores are available for download through the CalEnviroScreen website. We downloaded the data as a Microsoft Excel spreadsheet file and filtered the spreadsheet to show ZIP code data relating only to the San Diego region. We decided to use 12 out of the 20 indicators in our study: Ozone, Particulate Matter ≤ 2.5µm ($PM_{2.5}$), Asthma, Cardiovascular Disease, Low Birth Weight, Linguistic Isolation, Poverty, Unemployment, Educational Attainment (Education), Diesel Particulate Matter (Diesel PM), Traffic Density and Housing Burden. These indicators were chosen due to their potential influence with wildfire smoke. These indicators were used to perform linear regressions against wildfire particulate matter (WF $PM_{2.5}$) and respiratory hospitalizations.

CalEnviroscreen 3.0 Environmental Justice Variables

We utilized CalEnviroScreen 3.0 environmental justice indicators and respiratory hospitalization admissions in order understand the scope wildfires and wildfire smoke play in the potential role as an environmental injustice. Out of the 20 provided, we assessed 12 of the CalEnviroScreen 3.0 variables in our study that we felt were most pertinent in determining susceptibility related to wildfires and WF $PM_{2.5}$. The 12 variables can be categorized into three groups: Air Pollution/Air Quality, Health Susceptibility/Health Quality and SES. All three of these groups relate to vulnerability in some way: exposure, sensitivity, and adaptive capacity. Characterizing these indictors is an important step in understanding the distribution of exposure and susceptibility throughout the community (Rappold et al., 2012)

Exposure to environmental pollutants, such as Ozone, ambient PM $_{2.5}$, Diesel PM and Traffic emissions, can have negative health impacts. These pollutants influence air quality and have the potential to be modified with public policies.

For health susceptibility and quality, we investigated the following indicators: Asthma, Low Birth Weight and Cardiovascular disease. Pre-existing conditions can potentially cause more harm or make it more difficult to combat against an outside stressor such as a wildfire. In a recent study, researchers found that Public Safety Power Shutoffs (PSPS) had disproportionate adverse impacts among disadvantaged communities; for example, during a 2019 PSPS, those who relied on electricity for respiratory devices such as breathing aides or mobility devices such as electric wheelchairs faced significant challenges (Abatzoglou et al., 2020). Moreover, a recent studied demonstrated that elderly people, a population already considered vulnerable, who have pre-existing health conditions were at a higher risk and more susceptible to physical and mental health impacts (Masri et al., 2021). Lastly, multiple studies have suggested that wildfire $PM_{2.5}$

can cause higher rates of emergency department (ED) visits for asthma and cardiovascular disease.

Our SES group included Education, Linguistic Isolation, Unemployment, Poverty and Housing Burden. It has been clear throughout the environmental justice literature that the burden associated from air pollution and $PM_{2.5}$ disproportionately affect racial/ethnic and socioeconomic minorities (Marlier et al,, IN PRESS). For example, after evaluating multiple measures of community health, Rappold et al., 2012 found an 85% and 124% difference for asthma and congestive heart failure respectively between the top and bottom ranked counties and argued that socioeconomic factors were the most vital in defining community level susceptibility. The socioeconomic factors measured family and social support, education, income, community safety and employment.

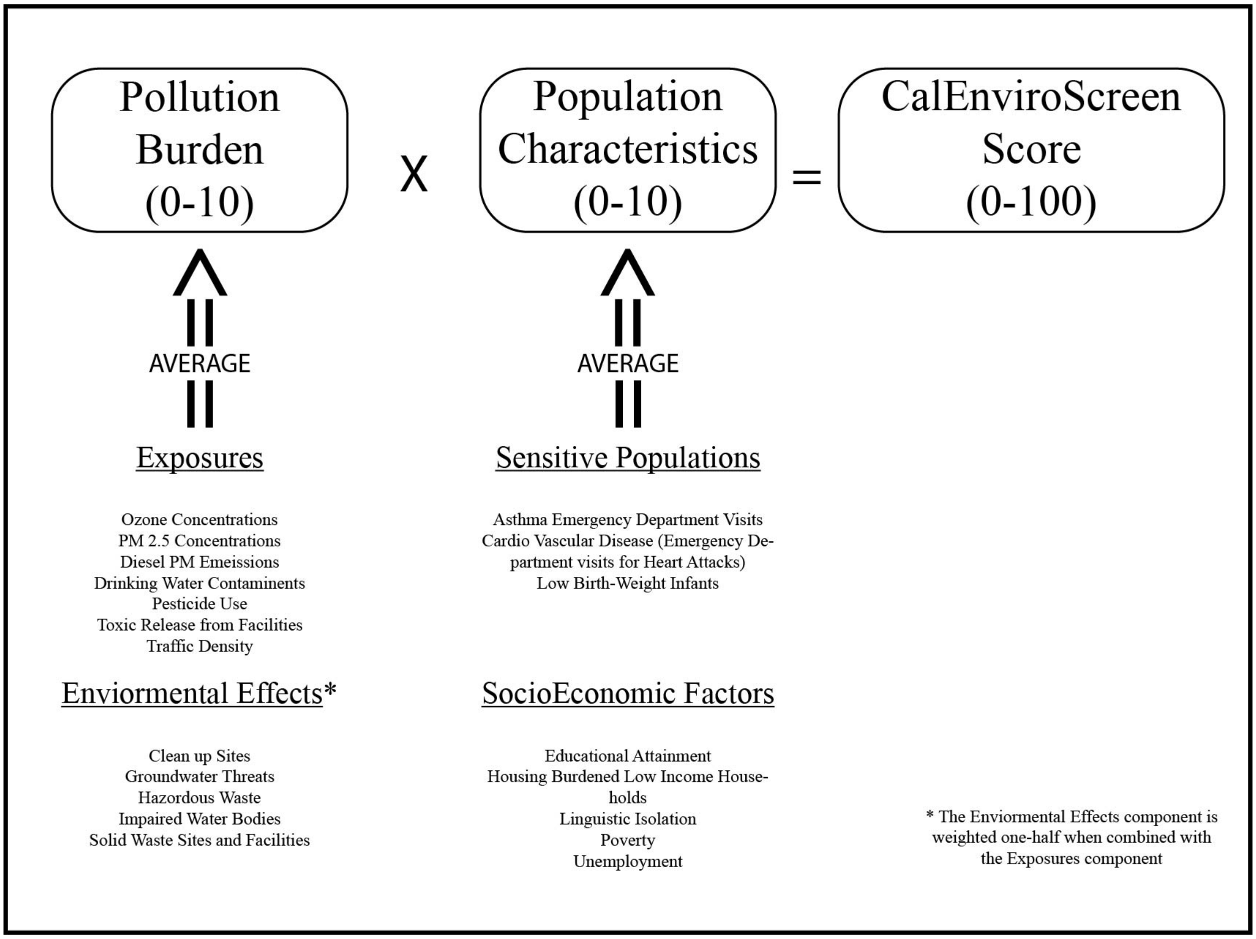


Figure 2: Flowchart demonstrating how CalEnviroScreen 3.0 calculates each Census Tract CalEnviroScreen Score.

Statistical Analyses:

All data analyses were conducted in R version 4.0.5 (R Core Team 2021). Using the dplyr R package (Wickham et al., 2020), the WF $PM_{2.5}$, wildfire specific respiratory hospitalizations and CalEnviroScreen spreadsheets were combined into one. To reduce repeating zeros and data, CalEnviroScreen environmental justice variables were aggregated at the mean level for each zip code. The R Stats package was utilized to perform linear regressions that compared both WF $PM_{2.5}$ and wildfire respiratory hospitalizations to CalEnviroScreen environmental justice indicators. To quantify the influence and statistical significance of WF $PM_{2.5}$ and hospitalizations with each indicator, the coefficients and 95% confidence intervals were collected and compared.

$$y = x * \beta_x + \beta_0 + \varepsilon$$

The equation above was used to compute the linear regressions, where β_0 is the intercept, β_x is the slope and ε is the error term. We focused on the beta coefficient (β_x) in our comparison analysis. In our study, the independent variables are the CalEnviroScreen indicators, the dependent variables are WF $PM_{2.5}$ and respiratory hospitalizations, and the slope is interpreted as the average change in 1 unit increase of an environmental justice indicator.

Spatial Mapping: ArcGIS

We used ArcGIS 10.8.1 (ESRI 2011) to visualize the differential exposure of WF $PM_{2.5}$ and differential susceptibility in respiratory hospitalizations in the San Diego region. Using CalEnviroScreen 3.0's data, each environmental justice variable was mapped to gain a visual understanding of which ZIP codes were experiencing different burdens. For differential exposure, we mapped out WF $PM_{2.5}$ concentrations and compared our results with each environmental justice indictor. Differential susceptibility was demonstrated through the comparison of wildfire respiratory induced hospitalizations and each individual environmental justice variable. Similarly, to differential exposure, we looked for areas of overlap to locate communities facing an accumulation of health burden.

Results

Descriptive Statistics

WF $PM_{2.5}$ displayed an average of 6.60 micrograms per meters cubed. The lowest concentration and higher concentrations were 0.00 and 96.75 respectively. Most ZIP codes in our analysis displayed concentrations higher than the WF $PM_{2.5}$ average, with the highest concentrations residing in the mid-northwest region of the County. Respiratory Hospitalizations produced an average of 4.10 hospitalizations, with a range of 0.00 to 23.00 hospitalizations. A high concentration of respiratory hospitalizations occurred within fire perimeters in the mid-northwest region and in the southwest region. These concentrations coincided with regions that are already experiencing higher rates of outside environmental justice indicators.

Exposure to Wildfire PM 2.5

Figure 3 illustrates high concentrations of WF PM $_{2.5}$ in the mid-northwest and southwest regions of the County. In comparison to the mean value (6.60), there was a significant increase in WF $PM_{2.5}$ in the areas directly west of the wildfires (Table 2). A small cluster of ZIP codes showed higher than average concentrations in the southwest downwind region. The ZIP code with the highest concentration (96.75) is located within the wildfire perimeters in the mid-northwest region of the County. Our spatial analysis reveals a pattern of burden in the southwest region and mid-northwest region of the County. All the environmental justice indicators except for Ozone consistently revealed clusters of burden in the southwest region. Furthermore, Ozone, Education, Linguistic Isolation, and Poverty illustrated higher than average concentrations in the mid-northwest region.

Respiratory Hospitalizations Attributable to Wildfire Smoke

Figure 4 illustrates a cluster of high respiratory admissions in the southwestern region of

San Diego County. In comparison to the mean value (4.10), there was a significant increase in hospitalizations in areas downwind of the wildfires and west of the wildfire perimeters (Table 2). The ZIP code (92065) with the largest admission count (23) overlapped with the wildfire perimeters in mid-county. Spatial analysis exhibits overlapping areas of burden in the southwest region of San Diego County. All environmental justice indicators have a high-density accumulation in southwest region except for Ozone (Figure 5), which demonstrates a low concentration in the Southwest region and high concentration towards the north and northwestern regions.

Differential exposure

We wanted to see if we observe systematic inequalities of WF PM $_{2.5}$. Table 3 summarizes our results for the effect of wildfire $PM_{2.5}$ on the 12 environmental justice indicators analyzed. Nine out of twelve indicators exhibit an inverse relationship with WF $PM_{2.5}$, while Ozone (4.48×10^{-5}, 95% CI: 3.11×10^{-5} – 5.84×10^{-5}), Education (0.012, 95% CI: -0.034 – 0.058), and Linguistic Isolation (0.016, 95% CI: -0.0090 – 0.041) demonstrate a positive correlation. Overall, we did not find strong evidence for environmental injustice through differential exposure. Table 3 shows a negative correlation with the majority of our environmental justice indicators. This overall negative correlation highlights that low SES and environmental justice indicators communities are exposed to lower levels of wildfire PM $_{2.5}$. High SES communities were in the immediate areas of the wildfires but did experience harsher exposure than low SES communities. Our evidence suggests that wildfire smoke exposure randomly affects San Diego communities and is blind to the structural inequalities and historical land use policies.

Differential Susceptibility

On the other hand, when we looked at the relationship between environmental justice indicators and respiratory hospitalizations, we found that communities who were experiencing higher levels of environmental justice indicators were systematically the ones who had higher levels of hospitalizations. In Table 4, we observe a positive correlation in all the corresponding environmental justice indicators except for Ozone (-0.64×10^{-5}, 95% CI: $-.0.00013 – 4.64 \times 10^{-6}$) and Traffic (-7.66, 95% CI: -18.76 – 3.44). Furthermore, there are significant relationships in respiratory hospitalizations with Cardiovascular Disease (0.14, 95% CI: 0.12 – 0.17) Linguistic Isolation (0.49, 95% CI: 0.40 – 0.85), Low Birth Weight (0.057, 95% CI: 0.043 – 0.072) , $PM_{2.5}$ (0.032, 95% CI: 0.0093 – 0.054) and Education (0.88, 95% CI: 0.72 – 1.04). The higher values observe suggest a higher proportion of negative impacts. Pre-existing conditions like Asthma (1.83) and social characteristics such as Education (0.88) produce harsher impacts and demonstrate that respiratory hospitalizations are influenced by SES variables. These results highlight that the 2007 wildfire smoke has environmental injustice implications through the differential susceptibility mechanism.

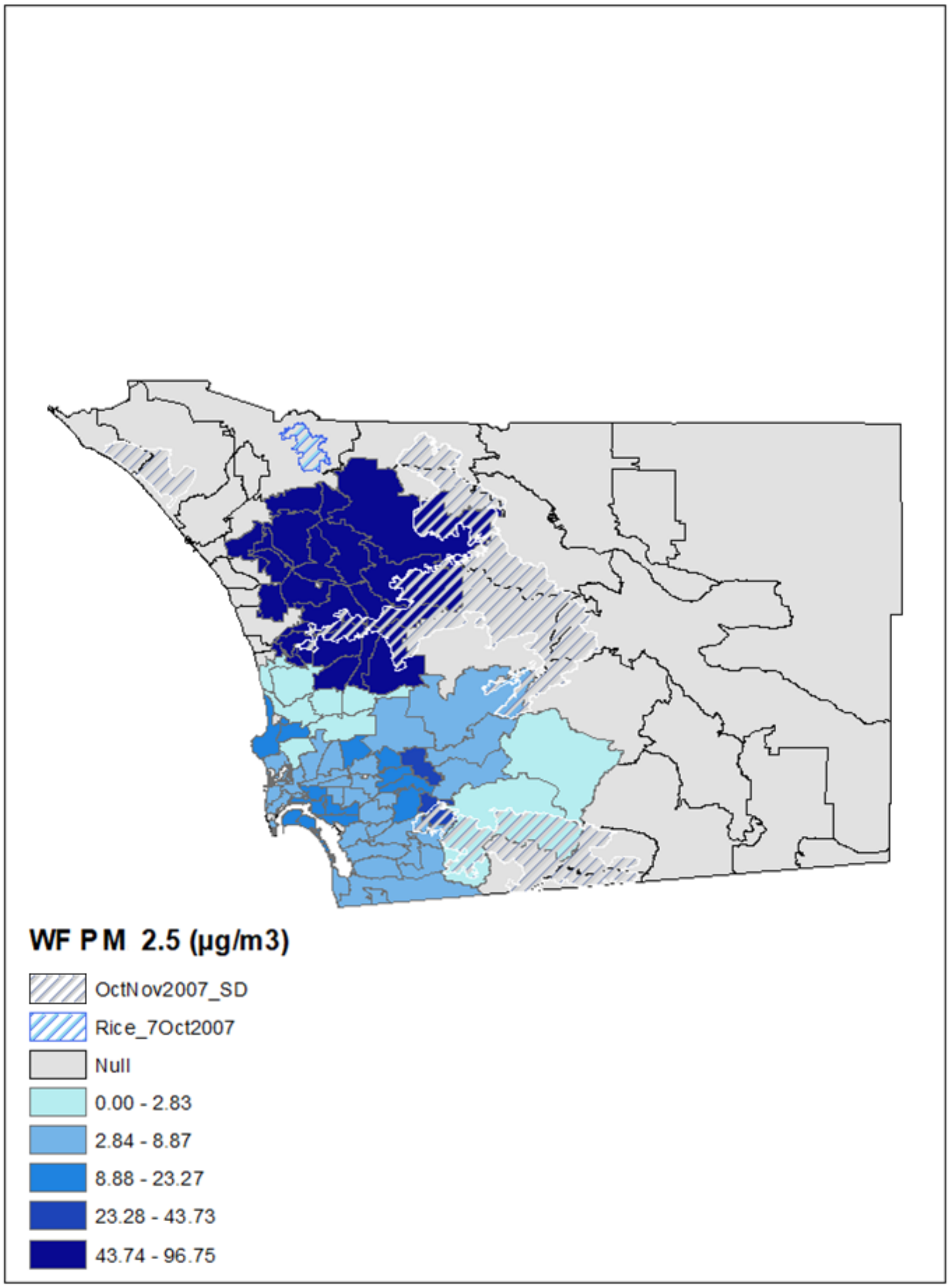


Figure 3: WF PM $_{2.5}$ concentrations distributed throughout San Diego Country during the 2007 Wildfire storm.

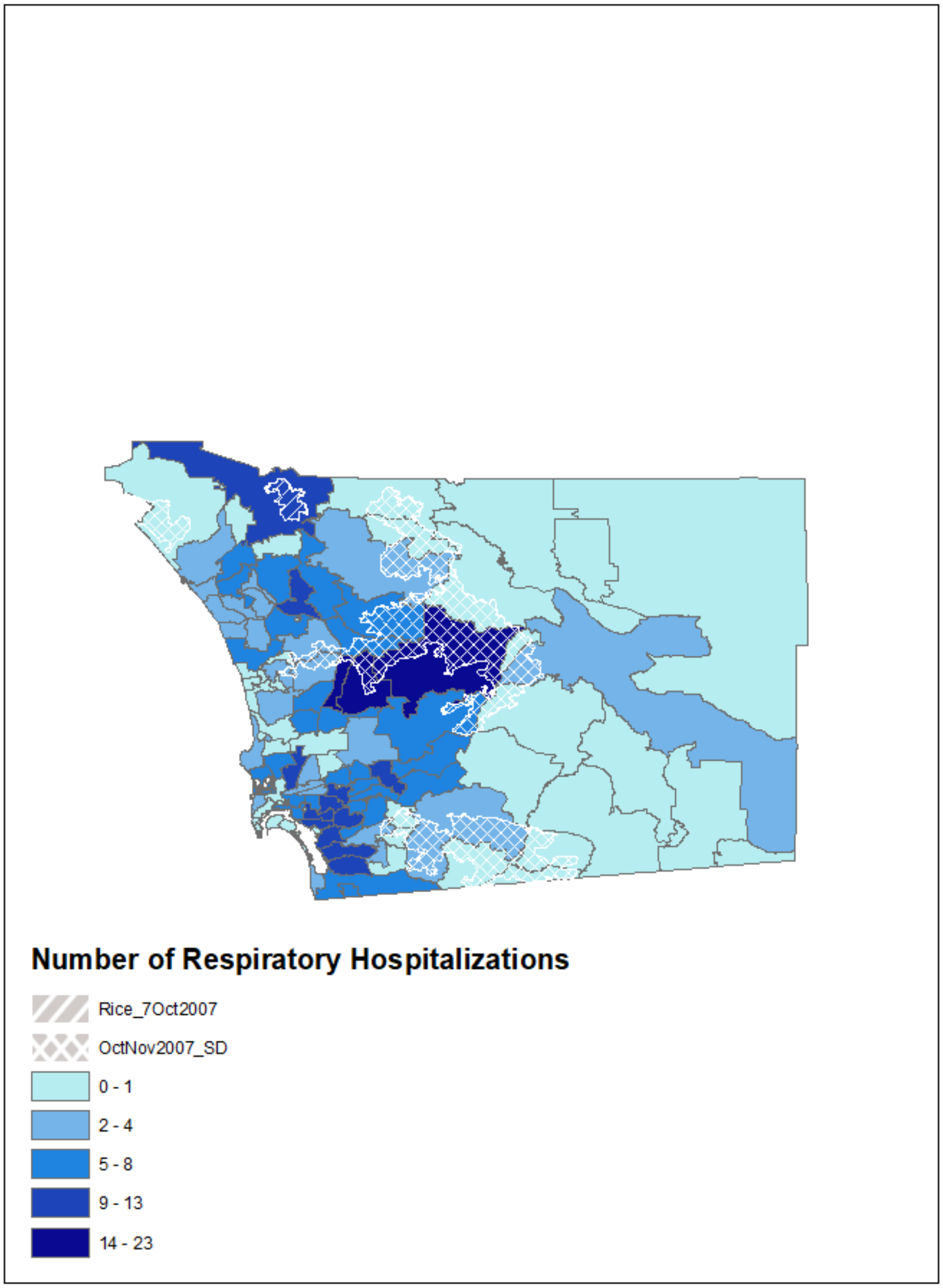


Figure 4: Excess Respiratory Hospitalizations attributable to WF $PM_{2.5}$ during the 2007 San Diego wildfire storm.

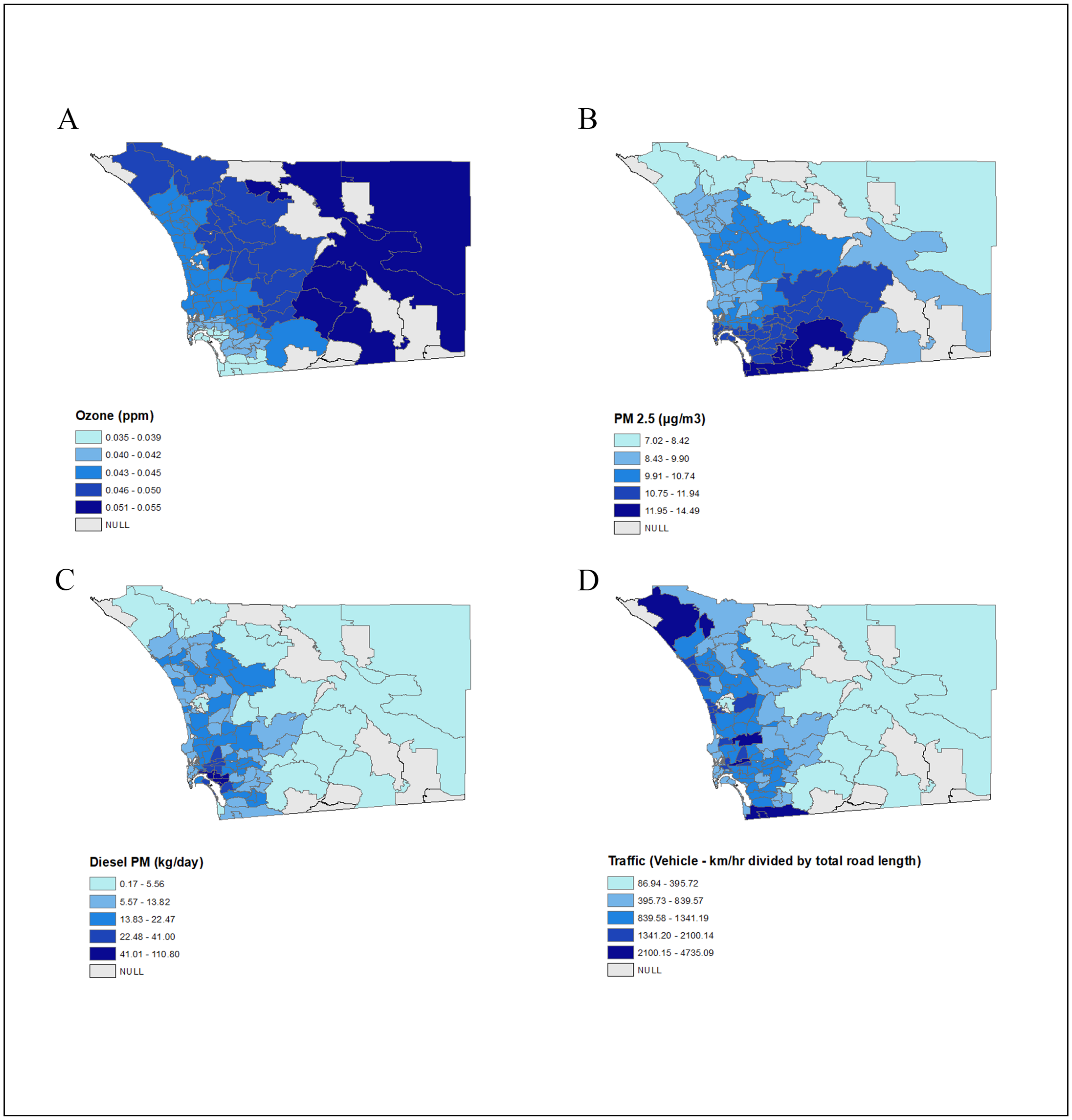


Figure 5: Spatial distribution of the air pollution and air quality indicator of A) Ozone B) PM $_{2.5}$, C) Diesel PM and D) Traffic Density.

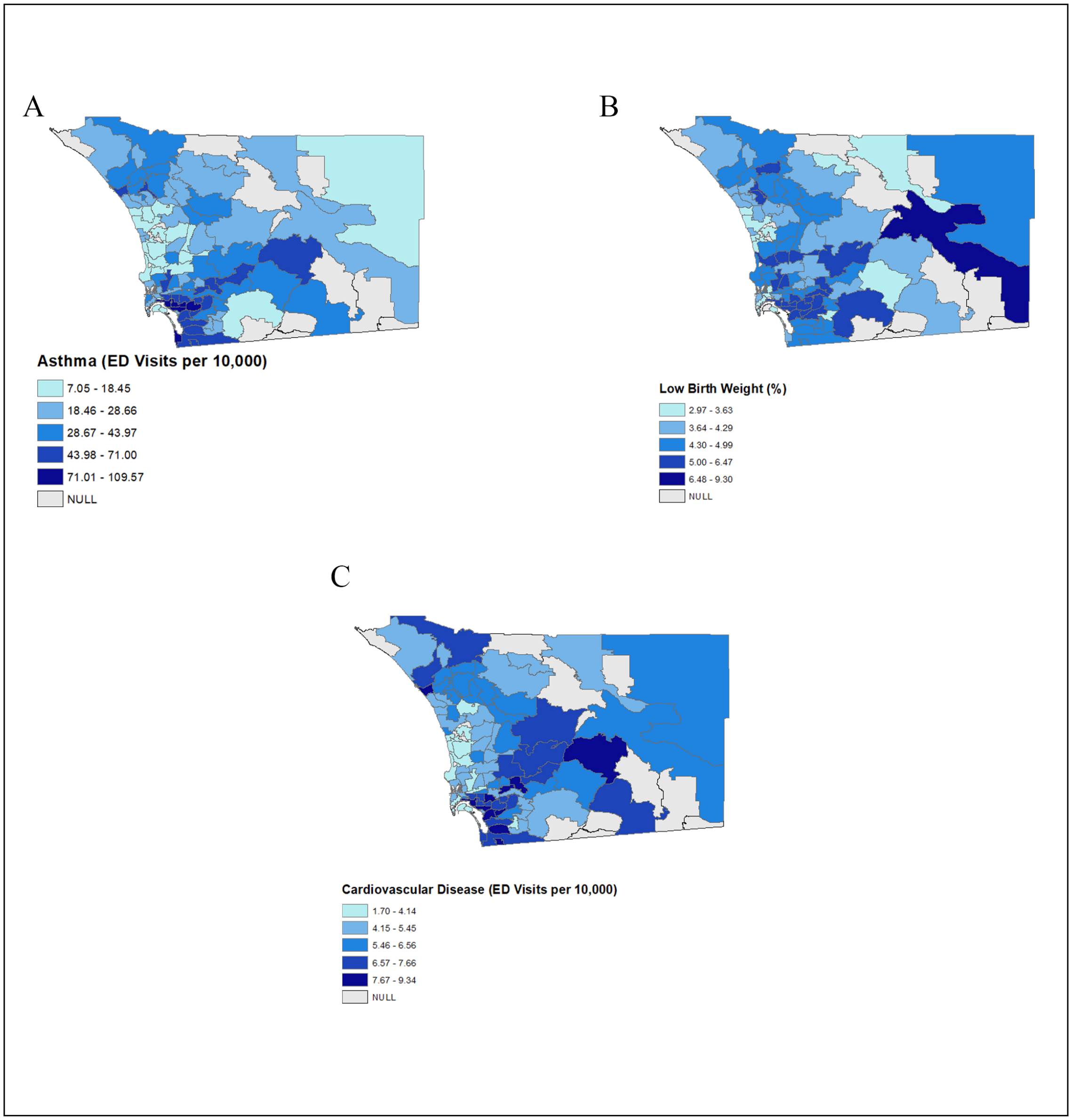


Figure 6: Spatial distribution of the Health Susceptibility and Health Quality indicator of A) Asthma B) Low Birth Weight and C) Cardiovascular Disease.

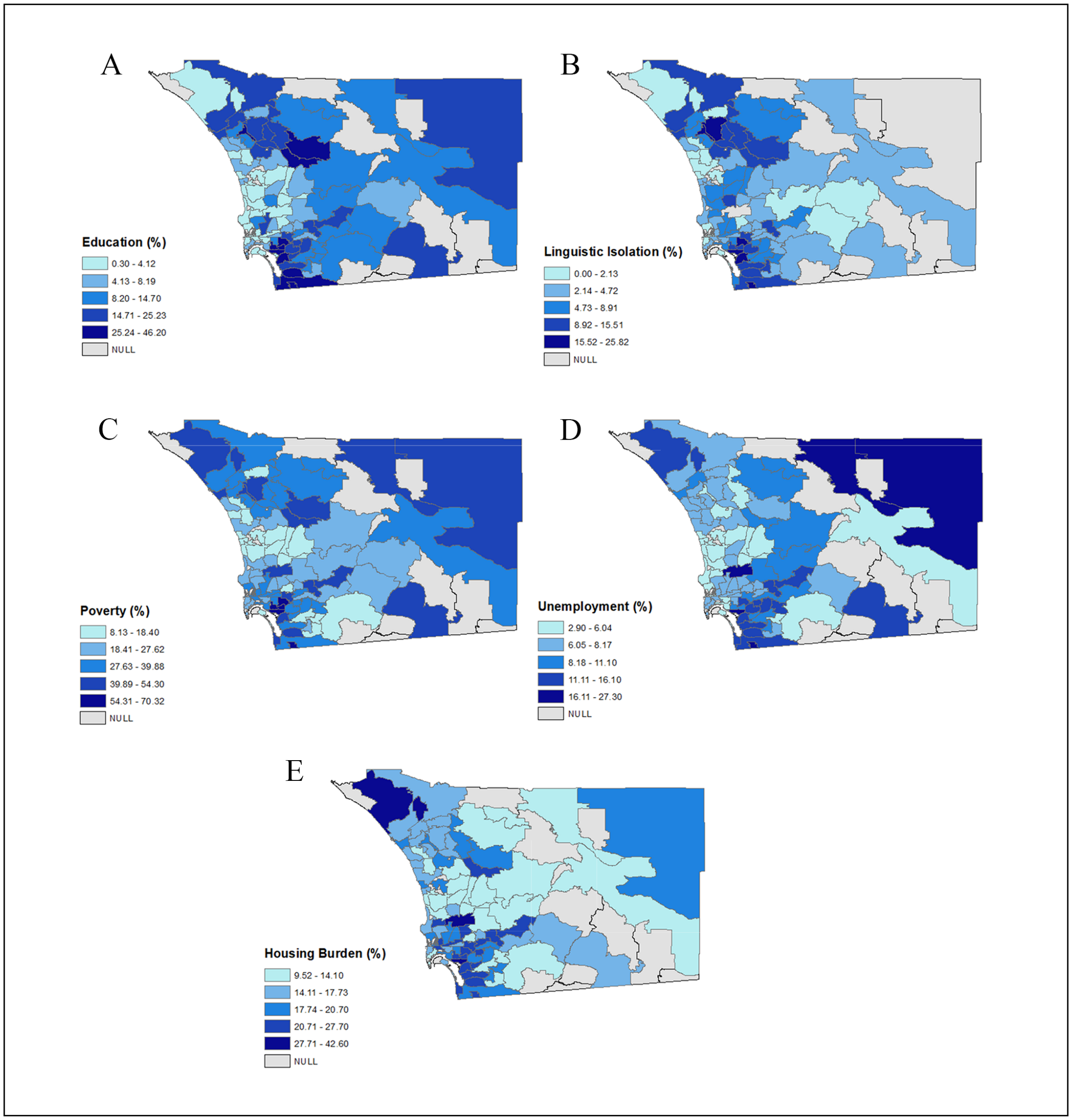


Figure 7: Spatial Distribution of SES indicators of A) Education B) Linguistic Isolation C) Poverty D) Unemployment and D) Housing Burden.

Table 1: Descriptions of each Environmental Indicator from CalEnvrioScreen 3.0.

Environmental Indicator	Description	Data Source
Ozone	Mean of summer months (May-October) of the daily maximum 8-hour ozone concentration (ppm), averaged over 3 years (2012 – 2014)	California Air Resources Board (CARB)
PM 2.5	Annual mean concentration of PM 2.5 over three years (2012 – 2014)	CARB
Diesel P.M.	Gridded diesel PM emissions from on-road and non-road sources for a 2012 July summer day (kg/day)	CARB, San Diego Association of Governments (SANDAG)
Traffic Density	Sum of traffic volumes adjusted by road segment length divided by the total road length within 150 meters of census tract boundary (2013)	California Environmental Health Tracking Program (CEHTP), California Department of Public Health (CDPH), US Department of Transportation and US Customs and Border Protection, SANDAG
Asthma	Spatially modeled, age-adjusted rate of emergency department (ED) visits for asthma per 10,000 (averaged over 2011-2013)	California Office of Statewide Health Planning and Development (OSHPD), CEHTP, CDPH
Low Birth Weight	Percent low birth weight (averages over 2006-2007)	CDPH
Cardiovascular Disease	Spatially modeled, age-adjusted rate of ED visits for acute myocardial infarction (AMI) per 10,000 (averages over 2011-2013)	OSHPD, CEHTP, Environmental Health Investigations Branch, CDPH
Educational Attainment	Percent of the population over age 25 with less than a high school education (5-year estimate, 2011-2015)	American Community Survey (ACS), US Census Bureau
Linguistic Isolation	Percent limited English-speaking households (2011-2015)	ACS, US Census Bureau
Poverty	Percent of the population living below two times the federal poverty level (5-year estimate, 2011-2015)	ACS, US Census Bureau
Unemployment	Percent of the population over the age 16 that is unemployed and eligible for the labor force (5-year estimate, 2011-2015) +	ACS, US Census Bureau
Housing Burden	Percent of households in a census tract that are both low income* and severely burdened by housing costs**(5-year estimates, 2009-2013)	Housing and Urban Development (HUD), Comprehensive Housing Affordability Strategy (CHAS), ACS, US Census Bureau

Data Source: CalEnviroScreen3.0

Table 2: Descriptive Statistics table for Environmental Justice Indicators.

Variable	Mean	Median	Min	Max	Standard Deviation
Ozone	0.044	0.043	0.035	0.055	0.0041
PM 2.5	10.47	10.37	7.02	14.49	1.35
Diesel PM	16.84	13.59	0.17	110.80	16.98
Traffic	1021.04	972.58	86.94	4735.09	665.22
Asthma	34.40	29.41	7.05	109.57	20.03
Low Birth Weight	4.54	4.53	2.97	9.30	0.89
Cardiovascular Disease	5.87	5.84	1.70	9.34	1.56
Education	12.21	9.46	0.30	46.20	10.05
Linguistic Isolation	6.67	5.41	0.00	25.82	5.52
Poverty	30.71	29.57	8.13	70.32	13.56
Unemployment	8.82	7.70	2.90	27.30	4.12
Housing Burden	18.19	17.19	9.52	42.60	5.68
WF PM 2.5	6.60	0.00	0.00	96.75	20.05
Respiratory Hospitalizations	4.10	3.00	0.00	23.00	4.37

Table 3: WF $PM_{2.5}$ linear regression coefficients with Cis.

Environmental Justice Indicator	Differential Exposure WF P.M. 2.5		
	Coefficient α	**Lower CI (2.5%)**	**Upper CI (97.5%)**
Ozone	$4.48x10^{-5}$	3.11×10^{-5}	5.84×10^{-5}
PM 2.5	-0.012	-0.016	-0.0067
Diesel PM	-0.096	-0.17	-0.020
Traffic	-2.47	-5.23	0.29
Asthma	-0.15	-0.24	-0.060
Low Birth Weight	-0.0017	-0.0045	0.0011
Cardiovascular Disease	-0.0039	-0.011	0.0030
Education	0.012	-0.034	0.058
Linguistic Isolation	0.016	-0.0090	0.041
Poverty	-0.017	-0.076	0.041
Unemployment	-0.022	-0.036	-0.0074
Housing Burden	-0.030	-0.053	-0.0072

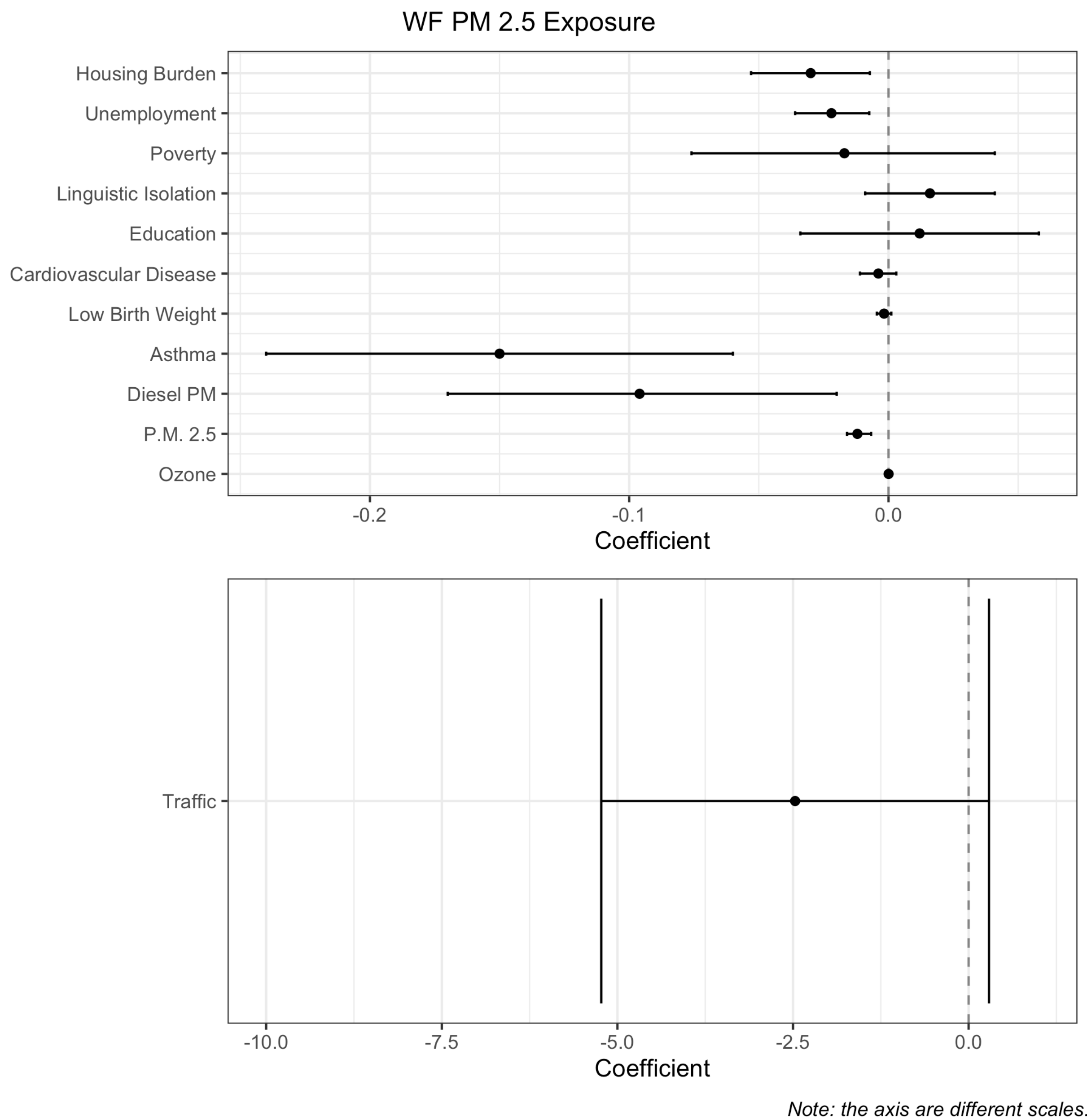
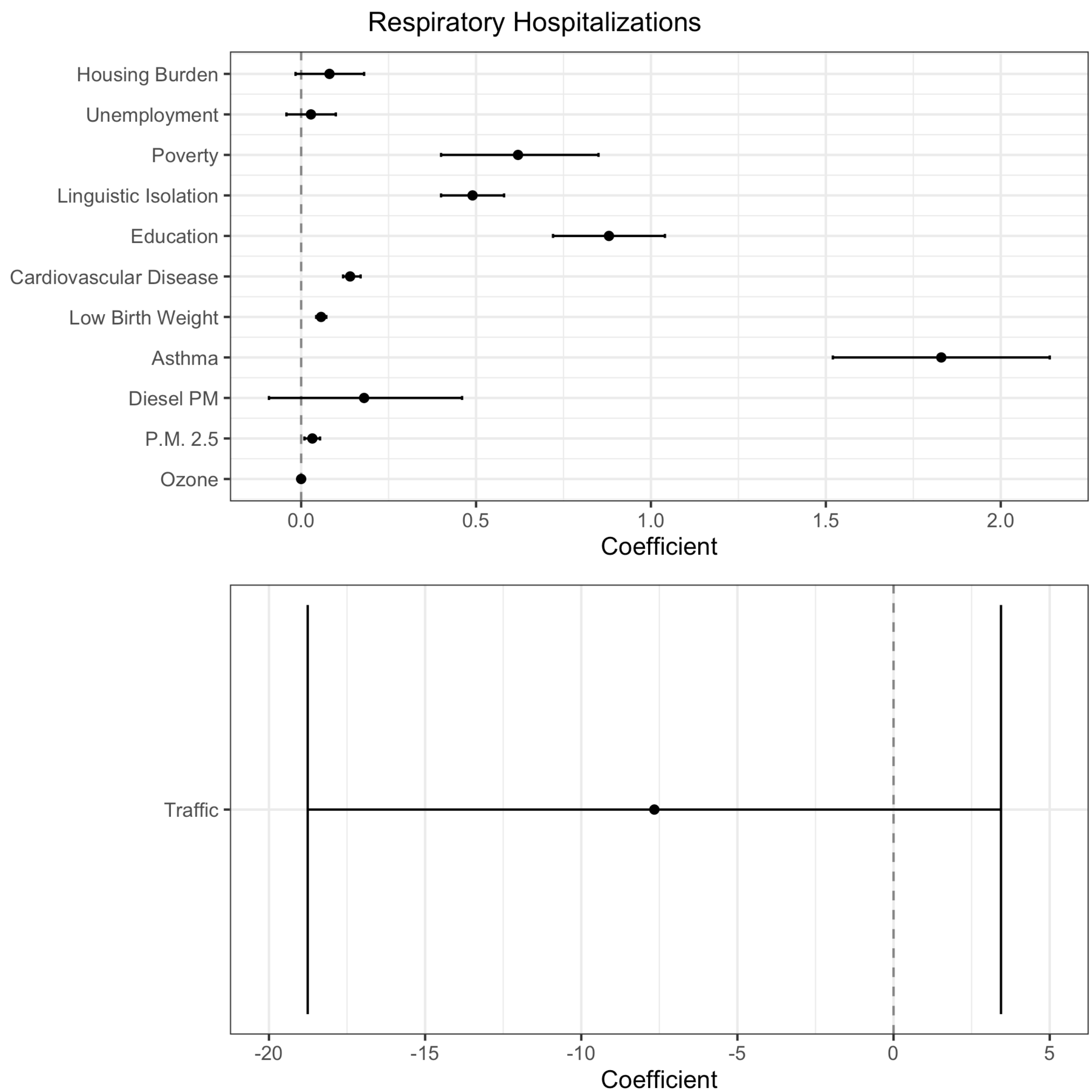


Figure 8: WF $PM_{2.5}$ exposure forest plots.

Table 4: Respiratory Hospitalization Coefficients with CIs.

Environmental Justice Indicator	**Differential Susceptibility Respiratory Hospitalizations**		
	Coefficient α	**Lower CI (2.5%)**	**Upper CI (97.5%)**
Ozone	-0.64×10^{-5}	-0.00013	4.64×10^{-6}
PM 2.5	0.032	0.0093	0.054
Diesel PM	0.18	-0.092	0.46
Traffic	-7.66	-18.76	3.44
Asthma	1.83	1.52	2.14
Low Birth Weight	0.057	0.043	0.072
Cardiovascular Disease	0.14	0.12	0.17
Education	0.88	0.72	1.04
Linguistic Isolation	0.49	0.40	0.58
Poverty	0.62	0.40	0.85
Unemployment	0.028	-0.042	0.099
Housing Burden	0.081	-0.016	0.18



Note: the axis are different scales.

Figure 9: Respiratory Hospitalization forest plots.

Discussion

For this study, we aimed at illustrating the environmental justice implications of wildfires using the 2007 San Diego wildfire as a case study. We assessed the relationship between WF $PM_{2.5}$ and respiratory hospitalizations with twelve CalEnviroScreen 3.0 environmental justice indicators. From our results, we did not find strong evidence supporting differential exposure as the mechanism contributing to environmental injustice. Wildfire smoke exposure randomly affects communities (and in some settings, low SES communities were actually less exposed to wildfire smoke) and is blind to structural inequalities. However, we did find a positive correlation between respiratory hospitalizations and the indicators. Hospitalizations attributed to WF $PM_{2.5}$ are correlated with environmental justice indicators. This suggests that differential susceptibility is the main driver through which wildfire contributes to environmental injustices.

Wildfire $PM_{2.5}$ tends to increase hospital admissions and has an impact on multiple environmental justice issues. Our study found that WF $PM_{2.5}$ and respiratory hospitalizations shared overlapping ZIP codes of concern, dominantly in the southwest region of San Diego County. These ZIP codes are downwind of the wildfire perimeters and cluster in previous communities of concern highlighted by CalEnviroScreen 3.0 data (Fig. 5, 6, 7). Figure 3 surprisingly did not show high concentrations of WF $PM_{2.5}$ in all the ZIP codes where the wildfires reside; some ZIP codes displayed no data values. Monitoring stations throughout the county were used to interpolate WF PM 2.5 concentrations and are not distributed uniformly. ZIP codes with no data were caused from the locations of the monitoring stations and the IDW method with a 20 km buffer described in Aguilera et al., 2020.

Overall, there is a positive correlation between the environmental justice indicators and respiratory hospitalizations. This supports our hypothesis that wildfire $PM_{2.5}$ influences a ZIP code's overall wellness in more than one way and can help predict which communities will be negatively impacted the most with future fires. During wildfires, it is often recommended to stay in-doors and/or at home as much as possible to decrease exposure to WF $PM_{2,5}$. Pre-existing conditions such as Asthma and Low Birth Weight and SES indicators demonstrated to be good predictors to those who would be most affected by respiratory hospitalizations. This information helps identify those who should be considered in our vulnerable population.

Implications

Our results highlight the importance of identifying vulnerable populations in the context of wildfires to design targeted interventions. In an exposed population, such as San Diego County, not every individual or community will experience equal amounts of wildfire smoke concentration or adverse effects. Furthermore, these individuals may not have the same resources or pre-existing health conditions. Vulnerability includes three main characteristics: exposure, sensitivity, and adaptive capacity (Davies et al., 2018; Paveglio et al., 2018). Adaptive capacity is the ability for an area to absorb, recover and mitigate from a hazard, such as a wildfire (Davies et al., 2018). Identifying vulnerable populations is essential in ensuring that early warning systems are providing the proper entities enough time to respond with appropriate actions. Linguistic isolation is an environmental justice indicator of importance. In our research, we found that those who were most affected by WF $PM_{2.5}$ and had high respiratory hospitalization rates also had higher rates of linguistic isolation. Siddiqui et al., 2014 argued that more than one-third of the county's population received no communication in regards to the 2007 wildfires, regardless of the efforts utilized by the local government: Reverse 911 calls, door-to-door communication, and television and radio communications. Reverse 911 calls were only given in English, so those who spoke a different language were unable to receive pertinent information.

Moreover, there is clear sense of mistrust and fear among the Hispanic and racial/ethnic minority populations; many were undocumented immigrants who were fearful of the government authorities and border patrol. (Siddiqui N, Andrulis D, 2014) These are all possible reasons to as why safety warnings were not received on time. This is important information to note when implementing early warning systems and relaying important warnings and actions, such as evacuation notices. It is essential that these warnings and messages are being received by the right populations in a timely manner and that we are implementing the most effective systems and platforms.

Early warning systems can constitute effective tools in achieving environmental justice. At-risk communities are prone to higher morbidity and higher mortality rates due to their social determinants of health (Davies et al., 2018;). With early warning systems, at-risk communities who have lower adaptive capacity can be identified and receive the necessary time to react and respond to precautionary measures. This in turn helps compensate for the social determinates of health and levels the playing field in health disparities and inequalities. Vulnerable populations have been previously identified before: individuals with pre-existing health conditions, children, and elderly people. Wildfires can exacerbate the health impacts of those who have pre-existing conditions. Also, children do not have fully develop health systems and PM can potentially compromise developing lungs and heart health. Lastly, the elderly tend to have declining/weaker immune systems and/or have other health conditions. The study presented identifies a region of high health burden and adds a level of specificity; policymakers should continue to provide resources to those historically sensitive populations but also should consider looking at these populations in this region in particular.

Other Studies

Some previous studies have also assessed the mechanisms that influence the environmental justice implications of air pollution. Similar to our results, Forastiere et al., 2017 found that differential susceptibility was the main driver in environmental injustice; evidence suggested that although high income residents resided closer to high traffic emissions, they are not as affected by the negative health impacts as compared to citizens from other lower social class categories.

In a spatiotemporal 2008 Northern California study focusing on wildfire smoke, researchers observed a linear increase for asthma ED visits and asthma hospitalizations with increasing concentrations to wildfire $PM_{2.5}$. They also found a stronger effect among women versus men and in adults in comparison to young children and the elderly (Reid et al, 2016). Wigtil et al. 2016 used a similar approach to ours and evaluated place and social vulnerability to wildfires by investigating social and biophysical factors. They found that on average, places with high wildfire potential have a lower social vulnerability than others; however, approximately 10% of all housing in these high potential areas exhibit high social vulnerability. Our results seem to be consistent among the wildfire risk literature and support the conclusion that differential susceptibility is the main contributor to wildfire environmental justice implications.

Limitations

It is important to discuss potential limitations of this work. Our study was interpolated at the ZIP code level; as a result, this data is generalized, and does not mirror what could be occurring at the individual level. Individual data could differ based on resources available/utilized to them; for example, those with air filters installed in their homes or at work may not experience the negative consequences of WF $PM_{2.5}$ in the same manner as those who do not have the same resources. Furthermore, this data was estimated using hospitalization data, which reflects where people live, so it is possible some individuals may have moved out of our area of study, or some could have been at work. As a result, there is potential for misclassification. There is also the possibility that smoke and air particulates were misclassified. In addition to the above, our hospitalization and WF $PM_{2.5}$ data illustrates data from 2007. It is possible that the data could have changed in the past 10 years, so there is a potential time limitation. We decided to use 12 out of the 20 indicators in our study, but it is worth mentioning that several other dimensions can drive inequalities associated with wildfire smoke exposure and related health impacts. Furthermore, there is a potential generalizability limitation; this may not reflect the same exact effect in other study areas. Although there are more recent wildfires in the San Diego region, we chose this specific case study because this wildfire event was a major fire and has widely available data that has already been collected. It will be interesting to explore in future studies the role of alternative environmental justice indicators and also to explore such mechanisms in other geographical contexts and wildfire events.

Conclusion

Using the 2007 San Diego wildfire storm case study, we found that wildfire smoke has environmental justice implications through differential susceptibility mechanisms by exacerbating the health burden. Our results revealed that the number of hospitalizations attributable to wildfire smoke were not randomly distributed throughout San Diego. Exposure to wildfire smoke in San Diego was randomly distributed and for some indicators even inversely correlated. Indeed, WF smoke exposure is blind to systematic and historical inequalities, such as redlining and historic urban planning policies. In the context of climate change, wildfires are predicted to become more frequent and severe. Future studies should investigate the environmental justice implications in other contexts and in different types of fires. Such information could be particularly useful to design smoke warning systems that may dedicate proportionate resources to most susceptible populations.

This thesis, in whole, is currently being prepared for submission for publication of the material. Duran, Elizabeth.; Benmarhnia, Tarik. The thesis author was the primary investigator and author of this material.

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