Wildfire Smoke Exposure in California: Public Health Impacts and Mitigation Strategies

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The Master’s Project

Wildfire Smoke Exposure in California: Public Health Impacts and Mitigation Strategies

By

Jiaxi Hou

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For the degree of

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In
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Abstract

Climate change projections show that wildfires are becoming more severe and frequent over the next few decades. In California, as a leader in environmental protection and resilience planning, there are still concerns about the impacts of wildfire. Several places such as Napa Valley, Los Angeles forests, and Yosemite National Park have been exposed to long-lasting wildfire damage. Wildfire smoke contains toxic pollutants such as particulate matter 2.5 (PM$_{2.5}$) that can cause negative health impacts on the public. It has been proved that these public health impacts are cumulative, and wildfire PM$_{2.5}$ can exacerbate pre-existing conditions. Therefore, there is an urgent need for better wildfire-related action plans that can mitigate the impacts of the wildfire on vulnerable communities. This research serves as a risk assessment report to examine the public health impacts of wildfire smoke exposure in California and determine the effectiveness of mitigation strategies. The methodology of the risk assessment follows the guideline provided by US EPA, which includes hazard identification, dose-response assessment, exposure assessment, risk characterization, and risk management. Specifically, analysis of publicly available data and literature, comparative analysis of wildfire smoke impacts of people receiving mitigation strategies, case studies of several public health impacts during wildfires, and analysis of wildfire smoke exposure sites and exposed populations are included to accomplish the risk assessment report. Results show that public health issues such as respiratory and cardiovascular illness are correlated with wildfire smoke exposure. The sudden increase in PM$_{2.5}$ concentration during wildfire season can lead to an increase in local hospital admissions. Indoor air filtration and using N95 masks can be two effective and accessible methods for residents to mitigate wildfire smoke exposure. Cities are implementing mitigation actions in resilience plans for wildfire itself but only a few actions address the smoke impacts. Recommendations for cities to have more inclusive adaptation and mitigation measures to wildfire smoke exposure include: 1) using the monitoring system to setup thresholds for PM$_{2.5}$ concentration in communities and developing methods to precisely identify vulnerable communities, 2) a further study about the correlation wildfire PM$_{2.5}$ and health impacts, 3) development of well-designed air filtrations systems and distribution of N95 masks, 4) publish stringent regulations to ensure outdoor workers are protected from hazards. These recommendations emphasize the importance of inclusivity and minimizing the disproportionate impacts of wildfire smoke exposure on vulnerable communities.
1. Introduction

Our living planet is now experiencing severe climate change. The global temperature is increasing due to the anthropogenic production of greenhouse gases. These gases are emitted into the atmosphere through burning fuels in energy and transportation sectors as well as other human activities (Fankhauser, 2017). As these gases accumulate in the atmosphere, global warming occurs from the greenhouse effect. The increasing temperature has led to many changes in the natural environment and, as a result, causes severe climate hazards. In the most recent century, evidence shows that the global temperature has been rising at a rapid rate. There have been nine hottest years in history since 2000 (Ahdoot and Pacheco, 2015). As we continue to produce more and more greenhouse gases into the atmosphere, climate change and its consequences will likely accelerate in duration and frequency.

The trapping of heat by greenhouse gases has led to many changes in the natural environment. Each year in the United States, environmental disasters take the lives of hundreds of people and cause injuries. Wildfire is one of the consequences of climate change. In California, people are now facing a growing forest and wildfire crisis. The size and intensity of wildfires in the state have increased dramatically accordingly.

1.1. What Causes Wildfires?

Extreme heat events caused by global warming associated with dry seasons have enabled an increase in the number of wildfires in recent years. Climate change projections suggest that extreme heat events will likely become more frequent over decades (Gingerich et al., 2015). Extreme heat events combined with dry weather conditions and high winds can increase wildfire risk. High winds can impact trees and power lines, which then spark a fire, especially in dry seasons. Lightning storms can also start wildfires. Uncontrolled campfires and arson are examples of human causes of wildfires.

The start and spread of wildfires require three key elements: heat, fuel, and oxygen. Heat sources come either from nature activities or human behaviors. Lightning strikes cause most natural
wildfires, but spontaneous combustion of dry fuel such as sawdust and leaves can occur. However, naturally caused wildfires only contribute a small percentage of the total number of wildfires in the United States. A National Academy of Science study shows that human behaviors are responsible for almost 84% of wildfires and 44% of total areas burned from 1992 to 2012. Indeed, during the 21-year time period, the human-caused wildfires usually can last three times longer than the natural-caused wildfires (Mercury Insurance, 2021; Balch et al., 2017).

After wildfires start with heat and fuel, they need a solid wind to spread the flames and cause millions of acres worth of destruction. High winds can accelerate the speed at which those wildfires expand. The rate of travel can reach 14.27 miles per hour due to the wind and high temperature. Indeed, high winds can also bring more fuels from other places, such as uphill, to create new fires. One of the examples can be the Thomas Fire in 2017 in California. The rate of fire traveled can reach a football field every second (Mercury Insurance, 2021; Balch et al., 2017).

Much of the State of California has protected wilderness from wildfires, but as human habitation has encroached on these protected areas, wildfires pose a significant danger to the citizens of California. For instance, the wildland urban interface (WUI) is the area that commonly experiences wildfires. It is the zone of transition between unoccupied land and human development and area where structures and other human development meet with undeveloped wildland or vegetation fuels (U.S. Fire Administration, 2021). As the WUI area continues to grow, there are now more than 46 million residents in the country who are suffering from WUI wildfire risks. California has the greatest number of houses in the WUI zone. The proportion of houses in the WUI relative to the total number of houses in California is about 30.1% to 45%. As a result, WUI fires have become an increasing problem in California. (U.S. Fire Administration, 2021) In 2020, as much as 25% of California was under extreme wildfire threat while more than 4 million acres were burned. The number of wildfires surpassed 8,200 (Stelloh 2020; Wildfires, 2021).

1.2. Wildfire Smoke in California

California has been one of the most affected states by wildfires. This has not been just a relatively recent phenomenon. Instead, California has been subject to wildfires for decades because of its
rapid urbanization and suburbanization into the countryside surrounding its vast urban centers. Table 1 documents some of the most significant wildfires in the state over the past two decades and the impact on life and structures:

Table 1. Major California Fires (Keeley and Syphard 2019)

<table>
<thead>
<tr>
<th>Year</th>
<th>Fire name</th>
<th>Month</th>
<th>Area (ha)</th>
<th>Cause</th>
<th>Lives Lost</th>
<th>Structures Destroyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Marble Cone</td>
<td>Jul</td>
<td>72 000</td>
<td>Lightning</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2012</td>
<td>Rush</td>
<td>Aug</td>
<td>110 000</td>
<td>Lightning</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2013</td>
<td>Rim</td>
<td>Aug</td>
<td>104 200</td>
<td>Campfire</td>
<td>0</td>
<td>112</td>
</tr>
<tr>
<td>2015</td>
<td>Rough</td>
<td>Jul</td>
<td>61 400</td>
<td>Lightning</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2003</td>
<td>Cedar</td>
<td>Oct</td>
<td>109 00</td>
<td>Flares</td>
<td>15</td>
<td>2 720</td>
</tr>
<tr>
<td>2007</td>
<td>Witch</td>
<td>Oct</td>
<td>80 200</td>
<td>Powerline</td>
<td>2</td>
<td>1 265</td>
</tr>
<tr>
<td>2017</td>
<td>Tubbs</td>
<td>Oct</td>
<td>14 900</td>
<td>Powerline</td>
<td>22</td>
<td>5 643</td>
</tr>
<tr>
<td>2017</td>
<td>Thomas</td>
<td>Dec</td>
<td>114 000</td>
<td>Powerline</td>
<td>2</td>
<td>1 063</td>
</tr>
<tr>
<td>2018</td>
<td>Woolsey</td>
<td>Nov</td>
<td>39 000</td>
<td>Powerline</td>
<td>3</td>
<td>1 643</td>
</tr>
<tr>
<td>2018</td>
<td>Camp</td>
<td>Nov</td>
<td>62 000</td>
<td>Powerline</td>
<td>88</td>
<td>18 804</td>
</tr>
</tbody>
</table>

There have been significant damages both to the natural habitat and human habitation due to wildfire. Property damage and loss of life are of great concern due to these wildfires. Since 2007, lives have been lost and more than 18,000 structures were destroyed by just 10 of the largest California wildfires (Keeley and Syphard, 2019). However, one often overlooked threat from these wildfires is the pollution due to so many wildfires which put off a massive amount of smoke, soot, and particles. Air quality was impacted significantly by the air pollutants released from wildfire smoke. Wildfire smoke, in general, is a mix of gases and fine particles from burning vegetation, building materials, and other fuels. Breathing in the smoke can have immediate health effects such as coughing, runny noses, headache, and asthma attack (CDC, 2013).
Current data indicates that the level of particulate matter 2.5 (PM$_{2.5}$) in the atmosphere in California during and immediately following these wildfires in 2020 reached a maximum of 453mg/m$^3$. The WHO states that 10mg/m$^3$ is the upper threshold of acceptable levels of PM$_{2.5}$ concentration for public health (CDC, 2013). In addition, the smoke released also contains fine and coarse particles, greenhouse gases such as carbon dioxide and methane, photochemically reactive compounds such as carbon monoxide, non-methane volatile organic carbon, and nitrogen oxides. These particles contained in smoke can travel thousands of miles, impacting air quality and posing public health risks far from the source of the fire. Figure 1 shows the wildfires from 1999 to 2012, and figure 2 shows the areas impacted by wildfire smoke.

![Map of wildfires in Southern California 1999-2012](image)

*Figure 1. Wildfires in Southern California 1999-2012 (Aguilera et al., 2021)*
Wildfires' particulate matter is more toxic than the equal number of doses from other sources, such as ambient pollution, based on recent animal toxicological studies (Aguilera et al., 2021). The reasons can be inflammation, oxidative stress, or increased respiratory infection by altering pulmonary macrophages activity. In general, particulate matter included in wildfire smoke is mostly carbonaceous, containing 5-20% elemental carbon and at least 50% organic carbon. It also has more oxidative potential compared to the particulate matter released from other sources. As a result, the compounds in wildfire smoke are likely to produce more free radicals and have greater potential to cause stress in the lung. It proves that there is a difference between particulate matter in wildfire smoke and not in wildfire smoke when assessing impacts on public health (Aguilera et al., 2021).

Figure 2. Wildfire smoke impact areas 1999-2012 (Aguilera et al., 2021)
In terms of environmental impacts, wildfires may lead to extreme heat events that may danger people in local areas. The extreme heat has become a significant hazard in the US and led to more than 7,800 deaths (Medina-Ramon et al. 2006). These events can impact human health in various ways, including by exacerbating health problems that already exist (White-Newsome et al., 2014). For instance, some people may get respiratory diseases after exposure to wildfire smoke. And these diseases may even get worse due to the extreme heat events related to wildfire. The Centers for Diseases Control and Prevention (CDC) conducted studies showing that exposure to extreme heat can promote discomfort, fatigue, heat cramps, dehydration, heatstroke, and hospitalizations. These negative impacts will later affect the productivity in communities resulting in economic impacts.

1.4. **Environmental Justice**

Environmental injustice means that environmental pollution is unequally distributed and released to the regions with poverty and communities with color and disadvantages. The EPA defines environmental justice as the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income (EPA, 2022). It argues for equal distribution of resources such as access to transportation and hospitals. For instance, common environmental injustice cases can be food swamps and food deserts. Food swamps refer to the area that is filled with fast food restaurants and food deserts meaning the community with limited access to affordable and healthy food options. Usually, environmental injustice is likely to happen in low-income and minority communities (Cooksey-Stowers et al., 2017).

Studies (Hajat et al., 2015) have shown that disadvantaged communities and minority groups are systematically more exposed to higher levels of air pollution (Hajat et al., 2015). As a result, they are impacted more by such sources of exposure (Benmarhnia et al., 2021). In California, climate change and air pollution disproportionately impact disadvantaged communities significantly (Morello-Forsch et al., 2011). Communities of color and poor residents are more likely to suffer from wildfire and breathe dirtier air afterward (Morello-Forsch et al., 2009). In most cases, residents in these communities even have less access to health care. In other words, they can hardly get proper medical services after getting exposed to wildfire. In addition, residents in these communities can hardly get access to mitigation actions. For instance, language barriers can
prevent them from receiving information and warning during wildfire events. During the 2007 San Diego Wildfire, about one-third of the population did not receive any form of communication about the wildfire and evacuation as a result of language barriers and a lack of communication (Siddiqui N et al., 2014). It is crucial for policymakers, government agencies, and organizations to consider environmental justice in making mitigation plans and identifying the vulnerable populations.

1.5. Study Area and Risk Management Approach

The purpose of this research project focuses on the potential threats wildfire smoke exposure can have on California’s public health. With limited information on how to apply mitigation strategies to these impacts in California, I reviewed the impacts that wildfire smoke had within California as well as the potential benefits that mitigation strategies may have. The concern is that exposure of some number of people to chemicals in wildfire smoke will cause health issues such as respiratory diseases, asthma, or birth effects. The project is organized according to the four steps to risk assessment published by the National Academy of Science in 1983: 1) hazard identification, 2) dose-response assessment, 3) exposure assessment, and 4) risk characterization (Masters, 1988). Followed by the four-step risk assessment process, a risk management analysis will be provided (Figure 3). To accomplish the goals, I utilize several case studies to determine the socio-economic status of communities near wildfire smoke exposure areas and populations that can be impacted by smoke pollution in California. There will be two kinds of case studies included in the project: case studies for individual wildfires and case studies for individual regions. The case studies of individual wildfires are used to determine the relationship between wildfire smoke exposure and public health impacts. And the case studies of individual regions are designed to analyze the effectiveness of local resilience and mitigation strategies in preventing wildfire risks.
1.6. **Motivation for project**

My motivation in choosing this specific topic came while I experienced wildfire smoke impact in my neighborhood. The change in climate conditions during wildfire periods can be observed clearly. People are advised to stay at home, but further recommendations are limited. Wildfire events are one of the deadliest impacts of climate change. In order to improve environmental management to reduce the level of wildfire smoke exposure to the population, recent studies (Fisk and Chan, 2017; Kodros et al., 2021; Lassman et al., 2017) have established some solutions for the air quality concerns related to wildfire smoke. There are many efforts to reduce risks before wildfires happen. They aim to develop models to better predict fire behavior, burn patterns, smoke composition, and particulate matter concentrations (Boby et al. 2010). However, there are only a few solutions provided for mitigation strategies during and post-wildfire. It is essential to reduce hospital admissions and deaths through proper interventions and regulations. So, the primary
motivation underlying this research project rests with the need for improved and effective environmental management techniques during and post-wildfire. Not only do environmental wildfire management techniques need to be developed, but techniques must be developed to mitigate the downstream effects on population health.

1.7. Research Questions

California is now facing an increasing number of wildfires in the past decade. And the trend is likely to continue into the foreseeable near future due to climate change. Several studies have been done to show the impacts and compositions of wildfire smoke on local regions. However, there is a lack of research conducted to show the impacts of wildfire smoke exposure on the environment and public health. My goals for this project are to identify the impacts that wildfire smoke exposure can have on the public health in California and analyze the benefits that mitigation strategies can have to address the health issues. My sub-topics are to review how wildfire smoke pollutants are different from other air pollutants. Additionally, the area of wildfire smoke exposure impacts during and after the wildfire season is determined as well as the relationship between wildfire smoke exposure and health issues. Using risk assessment analysis, I would also like to evaluate wildfire smoke exposure hazards and the mitigation and resilience strategies to remove and minimize the level of risks. By doing so, safer and healthier living conditions in California. Finally, the objective is to also provide recommendations to strengthen wildfire smoke mitigation strategies.

By doing this specific research project, it will give researchers and regulators a perspective on how wildfire smoke exposure can impact public health and the environment in California and how we should mitigate these exposures using proper strategies.

Main research question:

What impacts does wildfire smoke exposure have on public health in California and how should we use mitigation strategies to reduce those impacts?

Research sub-questions:
- What is the composition of wildfire smoke and what are the differences between wildfire smoke pollutants compared to pollutants from other sources?
- What impact does wildfire smoke exposure have on public health?
- What strategies can be done by residents to prevent the impacts of wildfire smoke exposure in California?
- Do existing county-level Wildfire Resilience Plans for cities mitigate the impacts of wildfire smoke exposure?

Data and research methods are discussed in each of the following analysis chapters. Overall, the data used in this project came from the current scientific studies of wildfire smoke and health issues. Impacts of wildfire smoke exposure both within and without California are discussed. Chapter 2 and 3 discuss the composition of wildfire smoke and its impacts on public health. Chapter 4 and 5 analyze several mitigation strategies to address wildfire smoke impacts. Several case studies are included in the project to analyze communities that are most vulnerable to wildfire smoke exposure.

Most of the discussion in this paper is about wildfire smoke impacts inside California. Cases outside of California do not reflect or guarantee that these events will or will not occur inside of California. However, studying these impacts, it allows policymakers to make wise choices and consider all negative aspects of wildfire smoke impacts.

2. Wildfire Smoke

This chapter focuses on analyzing the composition of wildfire smoke and the areas affected by wildfire smoke exposure during and after wildfire seasons. It aims to accomplish the first step of the risk assessment process, identifying the hazards. Hazard identification is the process of determining how the chemical is related to particular health effects (Masters, 1998). In this chapter, chemicals and substances in wildfire smoke are analyzed by comparing the composition of particulate matter in wildfire smoke and other pollution sources. Understanding the composition and affected areas of wildfire smoke is necessary to determine the threats posed to the public health.
What is the composition of wildfire smoke and what are the differences between wildfire smoke pollutants compared to pollutants from other sources?

2.1. Overview and Literature Review

To assess the impacts that wildfire smoke exposure can have on public health and the environment, it is essential to understand the composition contained in the smoke and pollutants that can cause negative effects on human health. Current studies about wildfire smoke composition often collect samples near the center of wildfire events (Aguilera et al., 2021; Reid et al., 2005; Boby et al., 2010). Wildfire smoke generally is a mixture of gases and fine particles from burning materials such as vegetation, building materials, and other sources. It is made up of small particles, gases, and water vapor. The majority of wildfire smoke composition is water vapor. And the rest contains or serve as a precursor for air pollutants such as carbon monoxide, ozone, carbon dioxide, complex hydrocarbons, nitrogen oxide, air toxins, and other particles (USDA, 2000; Balmes, 2018; Reid et al., 2016; Urbanski, 2014). These chemicals in wildfire smoke are known to have direct detrimental effects on human health and contribute to the healthcare burden of smoke-impacted areas (Black et al., 2017).

Among those contaminants, PM$_{2.5}$ in wildfire smoke can adversely impact human health and has been studied the most. During wildfire seasons, the smoke not only can significantly elevate the level of PM$_{2.5}$ concentration in local areas but also change the composition of PM$_{2.5}$. (Liu and Peng, 2018). PM$_{2.5}$ refers to particulates 2.5 μm in diameters or smaller and is a mixture of several chemicals such as organic carbon, aluminum, and sulfate. (US EPA, 2016). It poses threat to public health because it can penetrate deeper into the lungs, reaching the alveoli and entering the bloodstream (Black et al., 2017)

2.2. Research Methods

This section analyzes peer-reviewed studies to characterize the properties of PM$_{2.5}$ in wildfire smoke and the differences between PM$_{2.5}$ in wildfire smoke and from other sources. A hazard identification analysis in risk assessment is used to determine the wildfire-specific PM$_{2.5}$ and its negative impacts on public health. Analysis of PM$_{2.5}$ in wildfire smoke in California was obtained
from the case study of Southern California and the research conducted by Jia Coco Liu and Roger D. Peng.

2.3. Analysis
2.3.1. Comparison of PM$_{2.5}$ in Wildfire smoke and from other sources

The spread of wildfire smoke can alter the level of PM$_{2.5}$ concentration in local atmosphere which leads to potential risks to public health. This can occur during and after the wildfire seasons while the smoke keeps traveling to different regions. There have been multiple studies about the health impacts (these impacts will be explained later in the project under the public health section) caused by wildfire smoke exposure. However, the differences in toxicity of wildfire PM$_{2.5}$ as compared to other ambient sources of PM$_{2.5}$ are not well understood. A recent study shows that wildfire-specific PM$_{2.5}$ could be more harmful than an equal number of doses from other sources such as ambient pollution (Wegesser et.al, 2009).

Case study: Southern California

Southern California consists of ten of California’s 58 counties including the Los Angeles country, the second-most populous urban region in the United States. In 2018, Los Angeles had a population of 3.99 million people with a median household income of about $62,000 (United States Census Bureau, 2019). Residents in Los Angeles County experience high air pollution levels due to high transportation and industrial emissions. And Los Angeles County experiences the dry gusty offshore Santa Ana Winds (SAW) in Southern California after the dry season in summer and before the rainy season in winter. These strong winds can intensify wildfires after ignition and expand the wildfire as well as the wildfire smoke into a large area (Aguilera et.al, 2021). Indeed, they are responsible for fanning and spreading wildfires burning in WUI areas and transporting wildfire smoke to densely populated coastal areas (Aguilera et al., 2020; Aguilera et al., 2021).
The study by Reid et al (2005) conducted in Southern California compared the health outcomes of PM$_{2.5}$ from wildfire smoke in Southern California to PM$_{2.5}$ from other sources. In Southern California, other sources of PM$_{2.5}$ emissions include vehicular emissions, industrial emissions, and agricultural emissions (Reid et.al, 2005). In order to isolate the impacts of wildfire-specific PM$_{2.5}$, researchers applied statistical regression methods with instrumental variables, and they collected data from the regions affected based on the zip codes. There are 696 zip code regions within the Santa Ana wind impact region included in the study (Figure 3). Daily hospital admissions for respiratory diseases were collected in the study regions. Based on the observation, the place with the highest mean PM$_{2.5}$ concentrations was observed along with the coastal zip codes with high populations (Figure 3). And figure 4 shows the cases of respiratory admissions per 100,000 individuals. The overall patterns of the two figures are similar except in some urban areas and the Central Valley, where dust can be a factor in the situation (Aguilera et.al, 2021).
Figure 5. Mean values of PM rate in Southern California (Aguilera et.al, 2021)

Figure 6. Mean rate of Respiratory Admissions (Aguilera et.al, 2021)
The statistical method further explains the relationship between wildfire-specific PM$_{2.5}$ and hospital admissions in Southern California (Table 1). Based on the results, a slight increase (~10 µg) in PM$_{2.5}$ concentration is likely to increase the number of hospital admissions by 0.76%. In comparison, during the wildfire season, the wildfire-specific PM$_{2.5}$ could lead to a roughly 10% increase in hospital admissions based on the method of Spatio-temporal imputation, the highest among the results from the three methods used. The other two statistical methods show a 1.28% increase and a 3.0% increase in hospital admissions in wildfire seasons. The result suggests that wildfire-specific PM$_{2.5}$ estimated by the method is up to 10 times more harmful to public health than the ones from other sources. (Aguilera et.al, 2021).

Table 2. Effect of PM on hospital admissions results (Aguilera et.al, 2021).

<table>
<thead>
<tr>
<th>Fire upwind + strong SAW (1999–2012)</th>
<th>Regression model for respiratory admissions (rate per 100,000 people)</th>
<th>Approach used to isolate wildfire-specific PM$_{2.5}$</th>
<th>Seasonal Interpolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ coefficient</td>
<td>0.0014</td>
<td>0.0071 0.0013 0.018 1.00068 1.00061 0.0024 0.0055</td>
<td></td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(0.00077–0.0021)</td>
<td>(~0.0022 to 0.017) (0.00068–0.0002) (0.0064–0.030) (1.00049–1.00087) (0.30–1.0015) (0.0018–0.0030) (~0.00068 to 0.012)</td>
<td></td>
</tr>
<tr>
<td>% change with 10µg/m$^3$ PM$_{2.5}$</td>
<td>0.76</td>
<td>3.8 0.72 10 0.67 1.28 1.3 3.0</td>
<td></td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(0.42–1.1)</td>
<td>(~1.2 to 8.9) (0.36–1.1) (3.5–16.5) (0.48–0.86) (0.37–2.19) (0.97–1.7) (~0.37 to 6.3)</td>
<td></td>
</tr>
</tbody>
</table>

The results show that wildfire-specific PM$_{2.5}$ can lead to a more significant effect on public health than PM$_{2.5}$ from other sources (More discussion in 2.3.2). With the same amount of increase, wildfire-specific PM$_{2.5}$ can lead to a greater percentage change in respiratory admissions than non-smoke PM$_{2.5}$ can. Even though results from the three methods differ significantly and all of them have relatively wide confidence intervals, all the wildfire-specific estimations are above the non-smoker estimations.

2.3.2. Change of Composition of PM$_{2.5}$
In order to mitigate wildfire smoke exposure impacts, environmental scientists are developing models to determine why and how different types of vegetation burn. These models can help them better predict fire behavior, burn patterns, smoke composition, particulate matter concentrations, and so forth (Boby et al. 2010). One concern about the wildfire smoke is that it has the potential to spread into a relatively great area of regions to alter the composition of PM$_{2.5}$ in the local ecosystem. PM$_{2.5}$ composition can vary by region and season (US EPA, 2016). The spread of wildfire smoke can potentially modify the composition of existing PM$_{2.5}$ by region. The threat of public health risks may differ accordingly and cause residents to respond differently.

Jia Coco Liu and Roger D. Peng (2019) conducted a study to understand the changes in the composition of PM$_{2.5}$ components with and without the influence of wildfire smoke in the Western US by ecoregions. The study included 11 states including California for data collection from 2004 to 2009 during fire seasons. Based on the results, the PM$_{2.5}$ concentrations were about 110% higher on the path of smoke waves during the wildfire season, compared to the ones that are not on the path. It leads to significant changes in PM$_{2.5}$ composition. The organic carbon concentration in local PM$_{2.5}$ increased about 81% during the smoke wave days. In contrast, the fractions of other species in PM$_{2.5}$ during the smoke wave days all become smaller as well as the metals such as lead, magnesium, and selenium (Jia and Roger, 2019). A specific example could be that if the current organic carbon concentration in PM$_{2.5}$ was 50% during non-smoke days, when the smoke wave came, the fraction would then become 70% if the suggested increase in organic carbon fraction change is 20%.

There could be several factors that lead to the change of PM$_{2.5}$ composition during different smoke waves. Types of fuels burned such as a variety of vegetation types can greatly affect the composition of PM$_{2.5}$ during the wildfire smoke exposure period (Urbanski, 2008). Other factors such as weather conditions, humidity, and burning efficiency can also change the characteristics of wildfires. One example can be that the PM$_{2.5}$ composition during wildfire season in the Great Plains may be different from the composition in Northwestern Forested Mountains. The ecosystem in the Great Plains contains tallgrass prairie while Northwestern Forested Mountains are dominated by woodland vegetation. The two vegetations have different combustion efficiencies, which lead to a difference in PM$_{2.5}$ compositions during wildfire seasons (Jia and Roger, 2019).
The study further described why wildfire-specific PM$_{2.5}$ could be more harmful than PM$_{2.5}$ released from other sources. But limited studies have been provided about the correlation between change in PM$_{2.5}$ and public health risks. It is critical to have more studies in this field to further understand the public health impacts caused by wildfire smoke exposure.

### 2.4. Discussion and Conclusion

The first step in the risk assessment procedure is hazard identification. In this chapter, the substances in wildfire smoke that can impact public health are discussed. Wildfire smoke contains chemicals and particulates that may lead to negative health effects. And the most concerning composition of wildfire smoke is the PM$_{2.5}$ contained. Wildfire smoke exposure leads to significant increases in PM$_{2.5}$ concentration in the atmosphere, about 110% higher on the wildfire smoke pathway, which far exceeds the limitation set by the Air Quality Index by US EPA. The result from the comparative study shows that the PM$_{2.5}$ contained in wildfire smoke can be more toxic than the common PM$_{2.5}$ that existed in the air. And the composition of normal PM$_{2.5}$ can also be altered by smoke waves during wildfire seasons.

The common studies of wildfire smoke exposure tend to focus on individual wildfires and their results. Understanding the compositions of wildfire smoke and how they can change the environmental conditions and pose threats to public health are essential for finding mitigation strategies in California. But there is a lack of studies that have been done on this perspective.

Both studies included in this chapter suggest that wildfire-specific PM$_{2.5}$ can be more harmful to human health. The results demonstrated the complexity of PM$_{2.5}$ mixtures even if they are from the same source. So, they both recommend further studies in this specific field.

### 3. Analysis of Public Health Impacts and Risks

In this chapter, I focus on the impacts that wildfire smoke exposure can have on human health. The main health impact of the smoke exposure is respiratory diseases. It aims to accomplish the
second step of the risk assessment to determine the dose response and accomplish exposure assessment. Specifically, it aims to use illness and health records to determine how the public might be harmed by wildfire smoke exposure. This chapter focuses on the research question:

*What impact does wildfire smoke exposure have on public health?*

### 3.1. Overview and Literature Review

The more notable effects of wildfires upon the overall population are health and healthcare costs. The majority of the health risks involving wildfires are attributable to the increased density of airborne particulate matter, smoke inhalation, and heat exposure. One research study (Cleland et al., 2021) found that some counties in or near wildfires zones experienced as much as a 56% increase above baseline in respiratory and cardiovascular hospitals. The result is an immediate consummation of scarce community resources in the form of hospital supplies, equipment, and beds.

The long-lasting and fast expansion of wildfire smoke has caused exposure to harmful chemicals and PM$_{2.5}$ in communities that were not only close but far away from the fire. Public health threats caused by wildfire smoke exposure to communities introduce the potential for contamination of water, air, and soil. And air pollution accounts for the most public health threats during wildfire seasons. The major components of wildfire smoke are organic and elemental carbons as well as several gases such as carbon dioxide, carbon monoxide, and nitrogen oxide. And when the wildfire expands to the urban areas, the burning of industrial and building materials may lead to the release of other toxic chemicals. (Holm et al., 2021). As described in the previous chapter, varying concentrations of components in wildfire smoke may lead to different health issues during and post-wildfire seasons.

Literature suggests that short-term exposure to ambient PM$_{2.5}$ can lead to increased risk of acute respiratory and cardiovascular diseases (Balmes, 2018). There have been multiple studies showing the health impacts caused by wildfire smoke exposure. Generally, the public health outcomes of wildfire smoke exposure are mortality, respiratory morbidity, cardiovascular morbidity, birth
outcomes, and mental health (Reid et.al, 2016). Globally, an estimated 340,000-680,000 deaths per year are attributed to wildfire smoke and it has been found these health impacts are cumulative (Balmes, 2018; Black et al., 2017; Reid et al., 2016). The main problem of exposure to wildfire smoke is that it can affect the respiratory system through direct deposition in the lungs leading to local oxidative stress and inflammation. Specifically, when PM in the wildfire smoke directly entered the lungs, it could cause even more severe stress and inflammation (Holm et.al, 2021).

The US EPA published air quality standards for 24-hour PM$_{2.5}$ exposure to be 35 μm/m$^3$. Since exposure to PM$_{2.5}$ can cause severe negative health impacts, the EPA regulates PM$_{2.5}$ emissions to improve regional air quality. (Balmes, 2018; Ford et al., 2018) Even with government regulations monitoring PM$_{2.5}$ levels in California, the sudden release of wildfire smoke can easily exceed the standard to the level that can harm public health. Indeed, Ford et al (2018) found that fire-related PM exposure can offset the air quality improvements gained. An improper prevention method from wildfire smoke exposure could lead to severe health issues for the public through respiratory systems.

Natural factors can also facilitate the expansion of wildfire smoke and, therefore, cause negative health effects. In the previous chapter, there is a concern that SAW in Southern California can coincide with wildfire events. Aguliera et al. (2020) found that, even though SAW can lower the PM$_{2.5}$ concentration in the absence of wildfire, it can help to spread wildfire PM$_{2.5}$ from inland areas to densely populated regions and cause the PM$_{2.5}$ concentration surpass the national standard set by EPA (Aguliera et al., 2020).

There is a consistent amount of evidence showing the relationship between wildfire smoke exposure and general respiratory diseases (Reid et.al, 2016). Communities living in the exposure regions experience most of the negative health impacts. Air pollution caused by wildfire smoke exposure is increasing the risks in communities in California.

3.2. Research Methods
In this chapter, risk assessment methods are used to evaluate the potential health impacts of wildfire smoke exposure on the public. The hazard identification has been done in the previous chapter. Most of the harmful components in wildfire smoke move through the air. It is essential to identify the movement of smoke during wildfire seasons. By doing so, the populations that are exposed to the smoke can be identified. A dose response analysis in risk assessment determines the correlation between level exposed to PM$_{2.5}$ during wildfire events and increase in hospital admission. By doing the exposure analysis, I review the statistical testing methods that have been used to determine the relationship between wildfire smoke exposure and public health effects. An examination of potential health costs and economic losses will be applied by a brief risk cost-benefit analysis.

Geographical difference plays an important role in wildfire smoke exposure analysis. Wildfires happening in different regions can lead to a variety of severities. In this chapter, my goal is to apply case study methods of wildfires happening in both Northern and Southern California.

3.3. Analysis
3.3.1. Overview of Smoke Exposure in California

The burning of wildfire releases a large amount of smoke consisting of a mixture of chemicals, gases, and particulates. The indirect cost of wildfire smoke exposure is one that can be extrapolated to include more mid to long-term healthcare costs related to the effects of this smoke and PM$_{2.5}$ exposure. In fact, a study that examined the effect of wildfires on health and mortality attributed in excess of 2000 deaths directly to wildfires in one form or another (Liu et al. 2015). In order to get a relatively clearer view of the costs and impacts that wildfire smoke exposure may have on public health, it is essential to add a valuation to those hospitalizations and fatalities data to estimate the actual cost, which has been studied for years.

There is a growing need to incorporate the cost of damages to human health from exposure to wildfire smoke in the assessments of damages caused by wildfire. However, there is still a lack of literature available for policymakers and researchers to obtain these costs. In terms of the cost of damages to health, the average cost of illness estimated was $9.5 per exposed person per day (Richardson et al. 2012). And a study shows that an individual is willing to pay on average $84.42
to avoid one day of symptoms resulting from wildfire exposure. The number is calculated by the defensive behavior method to evaluate the actual health cost of wildfire smoke exposure.

However, in economic theory, people tend to avoid small expenses for high probabilities of big losses but to accept great losses with low possibilities. For instance, during wildfire seasons, some people may not wear masks to protect them from wildfire smoke exposure since they believe that they will not get respiratory diseases. In this case, it is affordable for them to pay $9.5 per day for protection from wildfire smoke exposure.

Data shows that the estimated health costs of wildfire in the Bay Area in 2018 were $7.8 billion. And the unhealthy air quality caused by wildfire smoke was long-lasting. During the 2020 wildfire season, the monthly maximum AQI reached above 100 for three straight months in the affected regions (Bay Area Economy, 2021).

3.3.2. Public Health Case Studies

A study conducted by Joshua A. Mott and his colleagues (1999) analyzed the public health impacts of the wildfire of 1999 in Hoopa Valley National Indian Reservation in northwestern California. By reviewing the medical records from the local medical center and doing survey interviews of residents, 289 out of 385 residents were observed. The result shows that, due to wildfire smoke exposure, medical visits to local medical centers for respiratory diseases increased from 417 to 634 visits, by approximately 52% compared to the previous year. And for the residents with pre-existing respiratory diseases, most of them reported that they got worsened symptoms during the wildfire season. A correlation between the number of patients associated with PM concentrations was strong, with $r = 0.74$ during the wildfire period (Mott et. Al, 1999).

The observations and analysis discussed in the Mott et al (1999) research were clear, but the analysis only focused on the community that was at the center of the wildfire region. Undoubtedly, residents in the community are the ones most vulnerable to wildfire smoke exposure. However, they cannot represent the whole population affected. It did not complete the study according to zip code to observe the effects in more regions. And the data collected in this case are partially from
surveys. It means that there could be potential biases in the data collection process. Overall, the numbers and results in the study provide clear evidence of health issues caused by wildfire smoke exposure (Mott et. al, 1999).

Further research on wildfire smoke exposure impacts was conducted by Delfino et al (2009) to find the relationship between respiratory hospital admissions and the wildfires in southern California in 2003. Smoke events during the wildfire period can dramatically increase the PM$_{2.5}$ level compared to the non-fire periods. The significant increase in PM$_{2.5}$ is associated with public health impacts, especially respiratory illness. Table 3 shows the PM$_{2.5}$ concentrations before, during, and after wildfire events. In all six counties included, the highest PM$_{2.5}$ concentrations were observed during the wildfire event. In San Diego County, the PM$_{2.5}$ concentration increased by 4 times during the wildfire period. However, in Riverside and San Bernardino, the increase was not as significant. Delfino et al hypothesized that the increase in PM$_{2.5}$ concentration can lead to public health impacts and respiratory diseases (Delfino et al., 2009).

Table 3. PM concentrations in San Diego Country during 2003 Wildfire (Delfino et al., 2009)

<table>
<thead>
<tr>
<th>Daily PM$_{2.5}$ levels (µg/m$^3$)</th>
<th>County</th>
<th>Los Angeles</th>
<th>Orange</th>
<th>Riverside</th>
<th>San Bernardino</th>
<th>San Diego</th>
<th>Ventura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before fires</td>
<td>Dates</td>
<td>01/10-23/10</td>
<td>01/10-23/10</td>
<td>01/10-20/10</td>
<td>01/10-20/10</td>
<td>01/10-24/10</td>
<td>01/10-22/10</td>
</tr>
<tr>
<td>Concentration (SD)</td>
<td>27.2 (12.4)</td>
<td>23.3 (9.6)</td>
<td>32.7 (14.7)</td>
<td>35.7 (19.6)</td>
<td>18.5 (8.7)</td>
<td>18.4 (8.3)</td>
<td></td>
</tr>
<tr>
<td>During fires</td>
<td>Dates</td>
<td>24/10-29/10</td>
<td>24/10-28/10</td>
<td>21/10-25/10</td>
<td>21/10-30/10</td>
<td>25/10-30/10</td>
<td>23/10-30/10</td>
</tr>
<tr>
<td>Concentration (SD)</td>
<td>54.1 (21)</td>
<td>64.3 (25.5)</td>
<td>42.1 (25.5)</td>
<td>55.1 (28.7)</td>
<td>76.1 (66.6)</td>
<td>50.1 (50.5)</td>
<td></td>
</tr>
<tr>
<td>After fires</td>
<td>Dates</td>
<td>30/10-15/11</td>
<td>29/10-15/11</td>
<td>30/10-15/11</td>
<td>31/10-15/11</td>
<td>31/10-15/11</td>
<td>31/10-15/11</td>
</tr>
<tr>
<td>Concentration (SD)</td>
<td>15.9 (5.5)</td>
<td>15.5 (10.2)</td>
<td>16.9 (6.6)</td>
<td>18.4 (8.3)</td>
<td>14.2 (7.2)</td>
<td>12.9 (4.3)</td>
<td></td>
</tr>
</tbody>
</table>

*PM$_{2.5}$ concentrations are calculated with equal weighting per zip code.*

There were a total of 40,856 children and adults hospital admissions included in the study, obtained from the California State Office of Statewide Health Planning and Development and collected from the periods before, during, and after wildfire events. Individuals living in the affected communities were studied. The levels of PM$_{2.5}$ concentrations were estimated according to zip codes (Delfino et al., 2009).

There was an average increase of 70µg/m$^3$ of PM$_{2.5}$ concentration during the wildfire period. And the increase in asthma admissions was about 34%. Among the populations studied, the most vulnerable populations were children and the elderly. However, the studies did not estimate the
relationship and correlation between hospital admissions and wildfire smoke exposure (PM$_{2.5}$ concentration increase). But the result still shows proof that wildfire-specific PM can result in higher hospital admissions (Delfino et. al, 2009).

The study conducted by Hutchinson et al (2018) further proves that respiratory diseases, especially asthma, were elevated during the San Diego Wildfire in 2007. Indeed, the authors aim to determine the health problems caused by wildfire smoke exposure, especially for vulnerable communities such as children, older persons, and people who already have respiratory diseases. There are 21,353 inpatient hospitalizations, 25,922 emergency department presentations, and 297,698 outpatient visits included in the study based on emergency department visits, hospitalizations, and outpatient visits from California’s Medical Program. As a result, it allows the authors to accomplish an analysis of the effects of wildfire smoke exposure on the vulnerable population. Data were collected in three time periods from October to December in 2007 during and after the wildfire event. The researchers can analyze the public health impacts during the time when the fire was most intense as well as the period after to determine the long-term health impact of wildfire smoke exposure (Hutchinson et al., 2018).

The result of the study shows that, when the fire was most intense, there was a 34% increase in the emergency department visits for respiratory diseases and 112% for asthma visits observed. Indeed, some public health impacts remained significant even after the peak of the fire period. The hospital visits for acute bronchitis were still 72% higher than the usual rate 5 days after the peak fire period. Among the vulnerable population, young children were impacted the most by the wildfire smoke exposure. Children aged 0-4 experienced a 136% increase in the number of visits for asthma while Children from 0 to 1 had a 243% increase (Hutchinson et al., 2018).

The study by Hutchinson (2018) shows strong evidence proving that wildfire smoke exposure can cause public health risks and increase the number of hospital admissions. It further provides information about the proportion of the vulnerable population that can be most impacted by wildfire smoke exposure. Young children in this case appear to be at the highest potential risk for respiratory diseases. Extreme weather events including wildfires can directly endanger children’s health. As the frequency of wildfire events keeps increasing in the past few decades, children are
now suffering from both physical and mental consequences. Indeed, there are studies performed in several countries that show that extreme heat events and wildfires can increase child morbidity and mortality. (Paulson et al., 2015) This result raises the concern about potential long-term negative health impacts on children’s health development. As a result, it is essential to plan to protect the vulnerable population from wildfire smoke exposure impacts.

It is important to evaluate the potential association between the impacts of smoke exposure in terms of illness and the perception of wildfire smoke as a hazard. A statistical hypothesis test has been provided to prove that there is a non-random association between the two variables (Fowler et al. 2019). Data were gathered through online and in-person surveys, targeting the population engaging in outdoor activities and older persons. There are a total of 2,237 samples collected. In the survey, five questions were asked: activity regions, activities, air quality notification, natural hazards, and health impacts. A statistical method, Fisher’s test was applied. However, the test result shows that there is not enough evidence to support that there is a non-random association between the two variables. Instead, the article provides a way to show how data should be used to find the mitigation strategies for wildfire smoke exposure. For instance, in order to achieve unbiased results, the authors suggest selecting the samples that can represent the population as a whole and exclude uncertain data from the samples. In my opinion, even though the result from the study shows no relationship, the process of analyzing the data is meaningful for future studies (Fowler et al. 2019).

### 3.3.3. Impacts of Air Quality on Public Health

Degradation in air quality caused by wildfire smoke can include the increase in PM$_{2.5}$ in the atmosphere as well as other toxic chemicals. The dose-response assessment shows that minor changes in air quality can lead to severe respiratory diseases such as asthma exacerbations in communities affected. In the studies discussed previously, the increase in hospital admissions is significant during and after wildfire season. And the areas affected by wildfire smoke exposure not only include the regions near the fire but also the communities far away from the fire.
Regional public health impacts caused by wildfire smoke exposure also led to cardiovascular health effects which include heart problems, heart attacks, stroke, and cardiac arrhythmia. These impacts are caused by chemicals and gases such as nitrogen oxides which are in the presence of wildfire smoke. An estimation shows that an additional day of wildfire smoke exposure in one month can lead to, on average, an 11.38 increase in the number of hospital admissions for respiratory diseases and a 3 increase in the number of circulatory illnesses in one county (Kingsland et al., 2022).

A more direct way to analyze the impacts of wildfire smoke exposure on health is to use economic losses as a measurement. USDA conducted six studies worldwide for health-related economic costs of wildfire smoke exposure. Table 2 shows the summary of the results. The economic costs of health impacts depend on the scale of the wildfire, the population exposed, and different types of health outcomes. The economic losses are calculated in two ways, which are the willingness to pay (WTP) and the cost of illness (COI). In the table, the economic cost calculated by WTP is higher than the result by COI. It implies that people are willing to pay more to avoid getting impacted. However, the costs calculated in table 2 are somehow underestimated since they do not include the cost of mortalities (Kochi et. al, 2010).

Table 4. Estimated Economic losses in 6 wildfires in the world (Kochi et. al, 2010).

<table>
<thead>
<tr>
<th>Name of the Fire</th>
<th>Estimated economic cost (2007 dollar value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fires in Amazon Between 1996 and 1999</td>
<td>$2,100,000 (annual average COI) $9,400,000 (annual average WTP)</td>
</tr>
<tr>
<td>Fire in Kaibab National Forest</td>
<td>$185,002 (COI and WTP mix)</td>
</tr>
<tr>
<td>2001 Chisholm fire in Canada</td>
<td>$2,706,782 (COI and WTP mix)</td>
</tr>
<tr>
<td>1997 Asian Haze in Malaysia</td>
<td>$5,422,798 (COI) $10,845,597 (WTP)</td>
</tr>
<tr>
<td>1997 Asian Haze in Singapore</td>
<td>$2,730,109 - $8,646,916 (COI) $5,460,220 - $17,293,831 (WTP)</td>
</tr>
<tr>
<td>1997 Asian Haze in Indonesia</td>
<td>$595,980,000 (COI) $1,191,960,000 (WTP)</td>
</tr>
</tbody>
</table>

There are also a host of different and, sometimes, competing tools that can be utilized to manage risk associated with the change in air quality due to wildfire smoke. This is because the effects on
public health due to air quality fluctuations are diverse in different regions, depending on the severity of wildfire smoke exposure. Different organizations may use different analysis tools to determine the economic cost of wildfire smoke exposure. For instance, a state organization tasked with managing protective habitats would measure the economic cost of wildfire based on equipment, material, and seasonality. Likewise, an organization tasked with providing a public health service would measure the costs based on medical services, number of admissions, and drug costs.

3.4. Discussion and Conclusion

Undoubtedly, chemicals from wildfire smoke have impacted public health significantly in California. Multiple well-developed studies have made the components in wildfire smoke publicly available. The most concerning component in wildfire smoke is PM$_{2.5}$. The level of PM$_{2.5}$ in the atmosphere in California during wildfire events far exceeds the upper threshold of acceptable levels published by WHO for public health. Peer-reviewed literature examining health impacts in California was necessary and valuable to determine what impacts of wildfire smoke pollutants within the state.

Public health impacts have been observed at higher rates in the communities affected by wildfire smoke exposure. Several case studies discussed in this chapter demonstrate the potential human health impacts caused by the exposure, including respiratory diseases as the major impact as well as asthma rates. The number of symptoms increased significantly in the affected communities during wildfire events. Even though the statistical analysis does not provide sufficient evidence showing the non-random correlation between wildfire smoke exposure and public health impacts, the study provides recommendations on how further statistical analysis should be performed.

With longer and more destructive wildfire seasons, more severe health impacts may be caused by longer exposure periods. The impacts have been observed in the communities in the smoke affected areas. The number of hospital admissions during and post wildfire season increases significantly. And there is strong evidence showing the association between the number of
admissions and wildfire smoke exposure. These diseases have already brought severe losses to the residences in the communities.

The information discussed in this chapter helps to finish the risk assessment process to determine public health impacts caused by wildfire smoke exposure. With detailed information about exposure to the hazardous air pollutants such as PM$_{2.5}$, public health risk is fully assessed. Evidence in this chapter helps to identify the chemicals in wildfire smoke as a hazard posing potential risks to public health. These chemicals have entered the air in California and are spreading widely. Based on the findings in this chapter, mitigation strategies are recommended to ensure the atmosphere is no longer polluted and public health is protected.

4. Mitigation Strategies

In this chapter, I analyze two mitigation methods that individuals can access to address wildfire smoke exposure. It aims to determine the actions that can be done by residents and accomplish the risk management procedure. The longer wildfire seasons and more destructive fires should alert people to focus more on how to protect themselves from negative health impacts due to smoke exposure.

What strategies can be done by residents to prevent the impacts of wildfire smoke exposure in California?

4.1. Overview and Literature Review

The previous chapters briefly describe the health-related costs of wildfire smoke exposure. Clearly, the best approach to resolving the costs of smoke exposure due to wildfires in California and beyond is to reduce or eliminate them. However, this is not a practical assumption to make, and therefore developing improved environmental solutions to such smoke exposure is the next best thing. One of the most effective and simultaneous solutions to address this particular risk exposure is in-home filtration. Several studies have proved that the installation of indoor air filtration can
reduce the hospital admission of respiratory diseases during wildfire season significantly. One literature finds that interventions applied to homes can prevent 47 to 261 respiratory hospital admissions in Southern California during the 2003 wildfire season (Fisk and Chan 2017). These data are referring to a specific wildfire from that year but it can be generalized across most wildfire smoke exposure. In effect, in-home particle filtration systems would conceivably reduce hospitalizations due to respiratory issues relating to smoke exposure by up to 80% or so based on that study’s data. However, the in-home filtration intervention system is costly so government support would be necessary for installing these filtrations in the areas precisely to mitigate wildfire smoke exposures (Fisk and Chan 2017).

In 2014, CDC published an article discussing the ways that people can protect themselves from wildfire smoke exposure. The purpose of the publication is to clarify the types of respiratory protection that can be used by the public. Besides the filtration system discussed previously, CDC analyzed the use of masks. It concluded that procedure masks tend to be no more effective than common paper masks in smoke prevention (CDC 2014). Instead, filtering half facepiece respirators (FHFR) such as the N95 masks can provide effective protection against PM released by wildfire smoke. And FHFRs are cost-effective so that the population can stock them at home for use during wildfire events. In order to further prove the statement, a filtration efficiency study was included as supportive evidence.

4.2. Research Methods

There are not many mitigation strategies provided by the government and researchers. In this chapter, I would like to discuss the two most commonly used mitigation methods in California: indoor air filtration, and using masks. Publicly accessible data, government reports, and peer-reviewed literature and studies are used to identify the differences in benefits that the mitigation strategies can bring to the communities. The analysis includes the reduction in hospital admission and air pollutants data as important measurements for the level of mitigation achieved.

4.3. Analysis

4.3.1. Mitigation Strategy: Indoor air filtration
Wildfire smoke not only affects the population exposed directly to the smoke but also impacts the ones that stay inside. Improving indoor air quality becomes an important target for mitigation strategies. There are basically two ways to improve indoor air quality: reduce air infiltration and filter indoor air. The commonly used way to reduce the outdoor air intake is sealing and positively pressurizing buildings. Avoiding outdoor air can effectively prevent wildfire smoke from getting inside the building. For instance, residents can seal doors and windows using towels and tapes to prevent leaks of smoke inside the building. Sealing buildings not only improves the indoor air quality and reduces air pollutant concentrations inside the building, but also enhances the energy efficiency by improving the life-span of air cleaner. However, it is usually hard for old buildings to properly seal. Indeed, sealing the building also prevents the carbon dioxide produced inside the building from getting outside. As a result, it may still impact indoor air quality (Davison et al., 2021).

On the other hand, filtering indoor air means removing PM and other particles from indoor air. There are two ways to accomplish the task. The first way is to build an air filtration system inside the building. Specifically, it means to upgrade the current air conditioning system so that it can have the function to remove air pollutants inside the building. However, the air conditioning system should be operated continuously to filter air in large spaces and multiple rooms. As a result, even though it may cost less compared to purchasing air cleaners, it has higher electricity usage (Davison et al., 2021).

The most commonly used method is the application of mechanical filters. Compared to the air filtration system, purchasing air cleaners is more flexible. Residents can select and purchase air cleaners based on their room sizes. And there are more selections in different types and prices. However, the efficiencies of particulate removal can differ greatly due to the differences in filters. Table 5 shows the actions that can be done during wildfire seasons to clean indoor air quality (Davison et. al, 2021).

Table 5. Summary of actions to improve indoor air quality during a wildfire (Davison et. al, 2021).
<table>
<thead>
<tr>
<th>ACTION DESCRIPTION</th>
<th>BETTER-SEALED BUILDINGS</th>
<th>BUILDING AIR FILTRATION SYSTEM</th>
<th>PORTABLE AIR CLEANERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close windows and doors</td>
<td>Improve the current air conditioning system</td>
<td>Select and purchase air cleaners based on the room size</td>
<td></td>
</tr>
<tr>
<td>Improve seals around windows, doors, and other opening</td>
<td>Run the air conditioning system continuously</td>
<td>Run continuously</td>
<td></td>
</tr>
<tr>
<td>Reduce outdoor air intake</td>
<td></td>
<td>Avoid ozone-generation units</td>
<td></td>
</tr>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td>Can improve the life-span of indoor air filters by reducing air pollutant concentrations</td>
<td>Cost less than purchasing air cleaning systems</td>
<td>More selections in different types and prices</td>
</tr>
<tr>
<td></td>
<td>Increase energy efficiency</td>
<td>Can filter airs in large spaces and multiple rooms</td>
<td>Can be moved easily</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Often include gas removal technologies</td>
</tr>
<tr>
<td><strong>CHALLENGES</strong></td>
<td>Hard for old buildings to seal</td>
<td>Only useful for buildings with high efficiency air conditioning systems</td>
<td>Many require multiple units in large spaces</td>
</tr>
<tr>
<td></td>
<td>May cause carbon dioxide and other pollutants to build up</td>
<td>Require frequent filter replacement</td>
<td>Noise produced</td>
</tr>
<tr>
<td></td>
<td>May lead to heat risks for the buildings without air conditioners</td>
<td>High electricity usage</td>
<td>Require frequent filter replacement</td>
</tr>
<tr>
<td></td>
<td>Need specific materials and professionals to seal</td>
<td>High electricity usage</td>
<td></td>
</tr>
</tbody>
</table>

CDC conducted a comparison showing the pollutant reductions from different mechanical filters. One of the studies was conducted to find the association between air pollution filtration and cardiovascular diseases. Data including 200 adult homeowners were randomly collected. The result shows that PM$_{2.5}$ concentration decreased by 57% after the implementation of air filtration.
It suggests that air filters can be a simple and useful method to reduce indoor air pollution. There are several other studies conducted for the same purpose provided by CDC. The mean reduction of PM$_{2.5}$ concentration using the air filter is over 50%. It indicates that indoor air filtration can be an effective way of pollutant reduction during wildfire season (Joseph et. al, 2020).

In order to further understand the potential health benefits of the costs of applying indoor filtration during wildfire season, Fisk and Chan conducted a study in six counties in Southern California in 2003. The health costs in the study were estimated by the exposed population, hospital admission rates, and effects on mortality. Based on the analysis, the estimated economic benefits from preventing respiratory hospitalizations with interventions during wildfire seasons range from $1 million to $5.8 million, and the economic benefits of reduction in mortality range from $75 million to $416 million. On the other hand, the cost of electricity in 6.92 million homes was estimated to increase by $110 million, approximately $16 per house. And if the costs of portable air cleaners are included in the cost calculation, the total intervention costs for the 6.2 million homes included in the study ranged from $1.7 trillion to $4.4 trillion. However, it is unlikely for all homeowners to purchase the air cleaners for only an approximately 10-day use during the wildfire season (Fisk and Chan, 2017).

The analysis shows that intervention during wildfire seasons could bring health benefits to the population exposed to wildfire smoke. However, since the fraction of the exposed population with a hospital admission attributable to wildfire smoke is small, the costs of implementing interventions in every household in the region far exceed the economic benefits of reduced hospital admissions.

### 4.3.2. Mitigation Strategy: Masks

Changes in air quality caused by wildfire smoke can include variations in PM in the atmosphere. These changes in air quality can result in public health issues such as respiratory diseases in the communities affected. Besides applying indoor interventions to the homes, another mitigation strategy is using masks. The BC Centre for Disease Control evaluated the effectiveness of using masks in communities in studies through literature reviews. In the case of the Hoopa Valley
wildfire in California in 1999, N95 masks and procedures and dust masks were distributed. However, there was no evidence showing that these masks can protect the communities from respiratory effects during the wildfire. The failure in this study could be a result of limited outdoor exposure, lack of proper testing methods, and the variability in the effectiveness of masks being distributed (Sbihi, 2014).

On the other hand, in the study conducted on the 2003 Southern California wildfires, the results showed that wearing masks during the wildfire season can help to reduce self-reported symptoms. Specifically, the result showed that by wearing the masks, the symptom rates of getting respiratory diseases were reduced by half compared to those not wearing the mask. After applying proper statistical methods to test the data collected, the difference appeared to be significant (Sbihi, 2014).

Another study was conducted by Kodros and his colleagues to quantify the potential health benefits following the use of face coverings by the general population as a means to reduce health risks from acute exposure to PM2.5 air pollution. While the use of face coverings such as surgical masks and N95 masks has been popular during the Covid pandemic, the understanding of the benefits of using them during wildfires remains limited. As a result, the study aims to develop the potential health benefits of using masks to reduce the amount of PM intake from air pollution. In order to do so, the authors performed a health impact assessment over the fire season in Washington State in 2012 to estimate the population-level health benefits of using masks during wildfire smoke exposures (Kodros et al., 2021).
During the wildfire period between July and October 2012, the air quality was impacted severely in Washington State (Lassman et al., 2017). The peak daily population-weighted PM from wildfire smoke exceeded 120 µg m\(^{-3}\) in the regions impacted the most. The result shows that there are significant differences in the effectiveness of different kinds of masks (Figure 8). The protection factor in the figure is calculated by a combination of reduction in hospitalization and amount of pollutant intake. Common natural-fiber face masks are ineffective in reducing pollutant intakes during wildfire seasons. The case study in Washington State showed that the reduction in hospital admission by natural-fiber face masks was only about 7%. In comparison, synthetic fiber masks provided moderate protection against a range of air pollutants from wildfire smoke. In the case of Washington state, the data proved that synthetic fiber masks can reduce 7% to 18% respiratory hospitalizations compared to the assumption of no face mask. The most effective face cover from the study is the N95 respirator as it can offer robust protection against PM pollutants. For instance, the use of N95 respirators could reduce respiratory hospital admissions by as much as 60% with the at-risk population wearing masks for two-thirds of the day during the wildfire period (Kodros et al., 2021).

4.4. Discussion and Conclusion
Based on the analysis, both in-door air filtration and using masks can positively help to solve the respiratory impacts caused by wildfire smoke exposure. Residents can easily get access to these mitigation products. The major concern about the public health impact of wildfire smoke exposure is the change in air quality caused by increased PM levels. A large amount of particulate matter is emitted in the wildfire smoke. Negative impacts on public health include respiratory diseases and asthma. Using in-door air filtration and masks helps to reduce the particulates intake by breathing, thus leading to protection from wildfire smoke exposure.

Based on the study completed by Fisk and Chan, indoor air filtration is a successful tool to reduce the air quality impacts caused by wildfire smoke exposure. The results from CDC show that, by applying the filtrations, the level of PM concentration is decreased significantly. Fisk and Chan evaluated the economic benefits and displayed the numbers of applying indoor air filtration to the residents in the impacted regions based on the assessment completed on six counties in California during wildfire seasons. The overall economic benefits based on reduction in public health impacts are significant, suggesting indoor air filtration can help to mitigate wildfire smoke exposure. However, the study also reflected that the cost of using indoor filtration is relatively high. As a result, it may not be affordable to all residents in the impacted regions.

Using masks can also be an effective mitigation tool in reducing public health impacts caused by wildfire smoke exposure. However, not all studies have consistent results proving the statement. CDC’s study about wildfires in 1999 in the Hoopa Valley did not provide evidence showing using masks can help to mitigate respiratory effects during the wildfire. It may be a result of problems in data gathering and a lack of proper statistical methods in analysis. Further studies show strong evidence of the correlation between using masks and a reduction in respiratory effects.

The study completed by Kodros further shows the difference in the effectiveness of different types of masks being used (Figure 8). It would have been beneficial for the residents to have an acute analysis that reflected the functions of different types of masks. The results show that N95 normally provides the best protection against air pollutants in wildfire smoke. Contamination in the smoke can hardly pass N95 and seriously impact the respiratory system. The other types of masks show similar results in preventing wildfire smoke exposure impacts.
The studies included in this chapter were most applicable to avoiding particulate matter being released as an air pollutant from impact respiratory systems. There could be more chemicals being injected into the atmosphere. There is still a lack of public understanding of how we can protect ourselves from these chemicals. Additional research is necessary to determine some public accessible methods for wildfire smoke exposure prevention.

This chapter determines the actions that can be done by individuals during wildfire seasons and meets the goals set by the risk management procedure. Both mitigation methods provided in this section can properly protect individuals from negative respiratory effects. Purchasing indoor air filtration can also act as a precautionary action. But further studies are needed to fully protect people from all chemicals released in wildfire smoke.

5. Wildfire Resilience Plan

The objective of this chapter is to assess regional resilience plans to mitigate wildfire smoke exposure in local communities in California using case studies. It aims to accomplish risk management procedures. It determines how to implement the mitigation and resilience plan. The information from this chapter will determine the effectiveness of the wildfire resilience plans by local governors and policymakers.

Do existing county-level Wildfire Resilience Plans for cities mitigate the impacts of wildfire smoke exposure?

5.1. Overview and Literature Review
Communities are often hit hard when it comes to environmentally damaging wildfire events. Residents living in the Bay area can see significant changes (Figure 10) in local air quality from their homes and have complained about the smell of smoke during the 2020 wildfire season. Air quality conditions around wildfire burning sites can be so poor that the government advised residents to stay indoors. The studies discussed in Chapter 3 found that residents living in the area affected by smoke are at risk of getting respiratory diseases such as asthma as well as other health impacts such as cardiovascular disease. And the individual mitigation efforts described in chapter 5 provide information about how individuals can protect themselves from wildfire smoke exposure. However, individual mitigation efforts may not be sufficient to perfectly prevent public health impacts caused by wildfire smoke. It is, therefore, crucial to determine how the government plays a role in managing wildfire activity and identifying the mitigation strategies to protect communities, especially the most vulnerable ones, from pollution from wildfire smoke.

For the most risk management strategies available in California, the solutions apply mortality and morbidity metrics to the risk management profile associated with air quality. All of these solutions focus on air quality specifically and therefore transfer directly over to air quality issues associated with wildfires within California. However, California also seeks to mitigate some of its air quality risks associated with wildfires through a different approach. This approach to air quality risk management and assessment undertaken by California environmental protection personnel focuses on vulnerabilities in the environment which encompass health as a factor rather than the focus of the assessment. This air quality risk management solution is referred as a “vulnerability assessment” in which factors such as climate change, climate sinks, fire seasonality, exposed rangeland, particulate matter levels, and existing land management strategies are all factored into a risk profile
Hence, each of these factors is provided with a corresponding risk value that is then compared to, weighted, and regressed into a risk level. This allows California to determine air quality standards and other regulatory benchmarks that govern its air quality and emission framework within the state.

In order to develop effective analysis, organizations such as EPA utilize data metrics that are fed with data collected from the market area in California. A data-driven model is a way to effectively undertake such analysis of air quality and certainly so with respect to wildfire-related particulates and pollution. The mode is derived from the Clean Air Act in which it integrates the sources of pollution into a cost profile based on emissions (EPA, 2021). All of the data is subsequently entered into a database and analyzed through the use of current states and future states based on the regulatory framework that governs each source category pollutant.

To assess and mitigate the impacts that wildfire smoke exposure poses on public health, proper resilience plans should be made to regulate the wildfires and smoke caused during the wildfire seasons. The state policymakers and agencies have bolstered efforts and increased investments in unprecedented ways over the past few years to make the Wildfire and Forest Resilience Action Plan to address the crisis. The actions required by the resilience plan are to address the key drivers of wildfires in California, significantly increase the pace and scale of forest management, and improve the resilience of threatened communities (Forest Management Task Force, 2021).

Based on the guidance provided in the Wildfire and Forest Resilience Action Plan, individual counties have established their own resilience frameworks to mitigate the wildfire impacts in the communities. There is an increasing need for wildfire mitigation as human activities have significantly impacted the natural cycle of the ecosystem in the surrounding areas. For instance, with human access to wildland areas, the risk of fire increases in the Sierra Nevada and Coast Range foothills due to a greater chance of human carelessness since about 90% of wildfires are human-caused (Forest Management Task Force, 2021). Fresno County, for instance, published its multi-hazard mitigation plan in 2007 and comprehensively updated it in 2018, including the efforts to be made for wildfire mitigation. It aims to reduce or eliminate long-term risks to people and property from hazards.
5.2. Research Methods

A case study of Fresno County is applied in this section to identify regional resilience plans used to mitigate wildfire and, as a result, reduce its potential health impacts on the public. The case study analysis includes the individual analysis of the community characteristics, vulnerability, and local government Wildfire mitigation Plans compared to goals set in California’s Wildfire and Forest Resilience Action Plan for Fresno County in California. Fresno County is located between the Yosemite National Park and Sequoia National Forest. As a result, it can suffer from wildfire smoke released from both Southern California and Northern California. Indeed, there are several minor wildfires happen in Fresno County annually as well. With a great proportion of outdoor workers in the region, Fresno County is one of the most smoke impacted counties in California.

5.3. Case Study: Fresno County

5.3.1. Community Characteristics and Vulnerability

Fresno County in California had a population of 530,000 residents with a median household income of about $50,000 (United States Census Bureau, 2019). The median age of the population in the county is 31.5. The community in Fresno County includes 49.5% of Latino and 13.9% of Asians, leading to an over 70% non-white community. Even though the median household income increased by 2.5% from 2017 to 2018, residents in Fresno County were experiencing an increase in the unemployment rate. The Bureau of Labor Statistics shows that the unemployment rate was 8.9% in 2019 and 10.8% in 2020 in Fresno County (U.S. Bureau of Labor Statistics 2020). The community is usually environmentally burdened as there is air pollution from surrounding freeways, wildfire smoke, poor water quality, and pesticide exposure (California Environmental Protection Agency, 2018).

There are three classes of wildfires that happened in Fresno County: understory fires, crown fires, and ground fires. Normally, naturally-caused wildfires in Fresno County burned at relatively low intensities, mostly consuming grasses, shrubs, and dead trees. But wildfire is still an ongoing concern in Fresno County. Historically, the wildfire season in Fresno County lasted from June to October of each year during the hot and dry periods. Since 2010, the wildfire season in the county
happened to get longer as the fire condition changed with a combination of high temperatures, intense sunlight, low rainfall and humidity, dry vegetation, and high winds. For instance, Santa Ana winds from southern California can cause small fires to move quickly, causing burning out of control (Forest Management Task Force, 2021).

In Fresno County, there are three principal areas that are impacted by wildfires significantly in history: West of Interstate 5, the San Joaquin River Watershed, and the Kings River Watershed (Figure 9). Each individual area has its own unique vegetation types, fire conditions, and communities. The weather condition in the West of Interstate 5 is low rainfall. And the vegetation type majorly consists of annual grass, oak woodlands, and brush. On the other hand, the San Joaquin River and the Kings River Watersheds have more diverse vegetation types including annual grasslands, oak woodlands, brush, and timber. (Forest Management Task Force, 2021)
An ignition analysis in 2004 determined four primary ignition sources including other and undetermined causing 535 fires, arson causing 311 fires, equipment use causing 315 fires, and debris burning causing 158 fires. In total, Fresno County experiences 120 to 200 fires annually in the state responsibility area and 1,400 to 1,600 fires in the local responsibility area. Figure 10 shows the history of fire in Fresno County from 1900 to 2017.

Figure 10. Fire History in Fresno County (Forest Management Task Force, 2021)

On the other hand, the extreme heat events in Fresno County are expected to increase in frequency and duration as well, which leads to the longer duration of the wildfire season. Data shows the average number of longest heatwaves between 1961 and 1990 was 2.4 days while the average number of longest heatwaves between 2050 and 2099 will be 13.1 days (University of California and California Energy Commission, 2020). In addition, the agricultural industry is heavily impacted by wildfire and smoke exposure. Residents living in Fresno County usually work outdoors to produce crops and livestock. Most of these workers are migrant agricultural field workers and construction workers, who are exposed directly to the wildfire smoke. Thus, they experienced health impacts such as respiratory diseases. Indeed, besides the exposure to particulate
matter from wildfire smoke, these outdoor workers also are exposed to particulate matter from agricultural burning and soil tilling (Jones et al., 2018).

5.3.2. Fresno County Multi-Hazard Mitigation Plan

Fresno County prepared the local multi-hazard mitigation plan in order to better protect people and properties in the County from environmental hazards in 2018. This plan evolved from the version published in 2007. It aims to reduce the potential risks from hazards and help policymakers to design mitigation activities and distribute resources. It was prepared to reduce environmental risks through community commitment and government participation. In the plan, wildfire mitigation has been listed as one of the most urgent targets. Along with the resilience plan, there were several loss prevention mechanisms already in place. The mitigation capabilities mean the programs and policies currently in use to reduce hazard impacts or that could be used to implement hazard mitigation activities. In relation to wildfire risks, the plan lists the following (The County of Fresno, 2018):

- Policy HS-B. 1: identify potential fire hazards and evaluate the effectiveness of prevention to reduce the risk to life and property
- Policy HS-B. 2: development in fire hazard areas should be designed and constructed in a manner to be fire-resistant.
- Policy HS-B. 3: development of fire-resistant vegetation in fire hazard areas, cleared fire breaks separating communities from vegetation
- Policy HS-B. 4: foothill and mountains subdivisions should have more than four parcels for safe and ready access for emergency equipment. Routes of escape for evacuations should be designed to meet fire safety needs.
- Policy HS-B. 5: adequate access for fire and emergency vehicles and equipment.
- Policy HS-B. 6: work with local fire protection agencies, the California Department of Forestry and Fire Protection, and the US Forest Service to promote the maintenance of routes for effective fire suppression and managing fire hazards.
- Policy HS-B. 7: firebreak easements should be developed to include access for firefighting personnel and emergency equipment.
- Policy HS-B. 8: review fire safety standards and responsibility.
• Policy HS-B. 9: year-round fire protection should be developed in foothill and mountain areas.
• Policy HS-B. 10: ensure existing and new buildings should have adequate fire protection to reduce potential losses.
• Policy HS-B. 11: develop water systems to meet fire flow requirements
• Policy HS-B. 12: promote installation and maintenance of smoke detectors
• Policy HS-B. 13: work with local fire agencies to develop high-visibility fire prevention programs

The policies listed above aim to develop proper wildfire mitigation actions to prevent losses of life and properties during wildfire events. In terms of actions to adapt and mitigate the impacts of wildfire, Fresno County prioritizes the mitigation action addressing wildfire hazards to the highest level. Nine new actions have been added to the resilience framework in 2018, compared to the 2007 version. Once these actions are adopted, the plan then faces the implementation stage. It will be accomplished by adhering to the schedules identified for each action based on its priority. Undoubtedly, the actions included in the resilience framework address the issue about wildfire hazards. Almost all the policies aim to protect residents from getting physically harmed by wildfire events. However, they did not specifically target the impacts of wildfire smoke exposure. There is no policy included to address the issue about wildfire smoke exposure. As a result, the resilience plan in Fresno County is not adequate and well-developed for wildfire smoke mitigation.

5.4. Outdoor workers

Workers in outdoor occupations such as agriculture, construction, and utility workers can be exposed to wildfire smoke. The effective smoke exposure can be greater for them than for the general public. And they could experience a higher risk of health impacts due to the poor air quality. Currently, California has adopted an emergency regulation set by California Division of Occupational Safety and Health (Cal OSHA) to protect these workers from smoke exposure (Navarro 2020). Cal OSHA determines PM$_{2.5}$ in wildfire smoke as the most harmful chemical to public health, and sets standards to mitigate wildfire smoke impacts on outdoor workers. The regulation is based on the Air Quality Index (Table 6). It is a method used by the U.S. EPA to
report air quality on a real-time basis. The AQI level is divided into six categories as shown in Table 6. The level of 150 is the threshold. If the AQI passes 150, it means that local air quality is no longer healthy for the public. Employers are required to closely monitor the exposure to PM$_{2.5}$ for worksites to protect the health of employees. The current local AQI level can be obtained through websites from agencies such as the U.S. EPA AirNow, the U.S. Forest Service, and the local air pollution control district. (Occupational Safety and Health Division, 2021)

*Table 6. Six Categories of Air Quality Index by Cal OSHA* (Occupational Safety and Health Division, 2021)

<table>
<thead>
<tr>
<th>Air Quality Index (AQI) Category for PM$_{2.5}$</th>
<th>Levels of Health Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 50</td>
<td>Good</td>
</tr>
<tr>
<td>51 to 100</td>
<td>Moderate</td>
</tr>
<tr>
<td>101 to 150</td>
<td>Unhealthy for Sensitive Groups</td>
</tr>
<tr>
<td>151 to 200</td>
<td>Unhealthy</td>
</tr>
<tr>
<td>201 to 300</td>
<td>Very Unhealthy</td>
</tr>
<tr>
<td>301 to 500</td>
<td>Hazardous</td>
</tr>
</tbody>
</table>

In the regulation, Cal OSHA requires employers to determine the concentration of PM$_{2.5}$ and reduce exposure if the AQI passes 151. When the local AQI level is reaching 150, it means that the air quality degradation in the area is severe and employers should be cautious about PM$_{2.5}$ exposure. They may need to prepare filtering facepiece respirators such as dust masks in worksites. On the other hand, when the local AQI level reaches 151, employers should control the harmful exposures to employees. There are several actions that they need to follow. The first action is to perform engineering controls. It means that employers should reduce employee exposure to PM$_{2.5}$ to less than a current level of 151 by mitigation actions such as providing enclosed buildings, structures, or vehicles where the air is filtered. And the second action is administrative controls. When engineering controls are not feasible or do not reduce employee exposure to PM$_{2.5}$, the employers should implement administrative controls such as relocating work places, changing work schedules, and reducing work intensity. And finally, employers should provide sufficient respirators such as N95 to all employees for voluntary use and encourage employees to use these respirators (Occupational Safety and Health Division, 2021). These actions are designed by Cal
OSHA to properly protect employees from wildfire smoke impacts. They can certainly reduce the exposure to poor air quality and therefore reduce potential health risks for workers. Therefore, it is critical to include them in mitigation plans.

5.5. Environmental Injustice

To determine vulnerability while making resilience plans, there are three characteristics included: exposure, sensitivity, and adaptive capacity. Adaptive capacity means the ability in the region to absorb, recover, and mitigate from a hazard (Davies et al., 2018). Identifying the vulnerable population is critical in providing warning systems to the proper communities to respond to emergency events and making mitigation plans to address environmental issues. Vulnerable populations include not only the communities impacted by the wildfire smoke exposure the most, but also the ones that suffer from environmental injustice. Siddiqui et al. (2014) indicates that there was more than one-third of the county’s population in Southern California did not receive communication during the 2007 wildfire, regardless of the efforts used by the local government: Reverse 911 calls, door-to-door communication, and television and radio communications. The reverse 911 calls in the region were only given in English. In other words, residents in communities who spoke a different language were not able to receive wildfire and evacuation information. And the only Spanish radio station in the local region never received any emergency notifications (Siddiqui N, 2014). There were several factors contributing to a lack of communication during the wildfire event, which is important to note in establishing the warning systems. It is essential that the warnings are received by right communities and populations to protect them from wildfire exposures.

Besides the lack of communication, economy in communities also serve as a factor contributing to environmental injustice. Low-income communities may not have sufficient funds to protect themselves from wildfire events, such as cutting bushes and trees, purchasing air filtrations, and getting insurance. They may also experience a lack of support to modify from wildfires (Davies et al., 2018). Masri et al (2021) found that rural areas usually exhibited higher rates of wildfire
burning in history. And these rural areas share the same characteristics: poverty, unemployment, low-income residents, low education, and a lack of communication methods (Masri et al., 2021).

Policies and mitigation strategies intended to modify wildfire risks and vulnerabilities can vary in effectiveness. For instance, insurance is typically only affordable to those with higher income or home-owners rather than those who rent (Davies et al., 2018; Wigtil et al., 2016). As a result, communities may be experiencing the same amount of wildfire smoke exposure but suffer worse health impacts and health burdens. Several studies suggest that wildfire vulnerability is spread unequally throughout the communities. People living in low-income communities, with pre-existing health conditions such as asthma or cardiovascular disease, and from minorities can face more severe impacts (Davies et al., 2018; Reid et al., 2016; Wigtil et al., 2016). Low-income communities do not have the capability to recover quickly from wildfire events. And residents with pre-existing health issues may be more susceptible to the negative health impacts and risks from wildfire smoke exposure (Rappold et al., 2012).

It is important to explore different factors that can influence the vulnerability. Investigating the vulnerabilities would allow policymakers and local government agencies to identify at-risk populations and regions. As a result, proper resilience plans can be made to protect people and properties from wildfire risks.

5.6. Discussion and Conclusion

Residents in Fresno County suffer from severe wildfire events and experience loss of life and properties. Individuals living in regions within West of Interstate 5, the San Joaquin River Watershed, and the Kings River Watershed are more likely to have negative health impacts from wildfire hazards than the ones in other regions of Fresno County. Table 9 identifies the population which is most vulnerable to wildfire hazards. Great health risks from negative impacts of wildfire smoke exposure will also affect residents in Fresno county significantly. Data shows that there is a huge number of workers in Fresno county who are field workers and construction workers. As a result, they can be exposed to wildfire smoke and experience health complications such as respiratory diseases. These workers can also suffer from extreme heat released by wildfires.
(National Farm Worker Ministry 2017). Cal OSHA has published regulations to protect outdoor workers from wildfire smoke impacts. There are several actions that employers could choose to implement, including engineering controls, administrative controls, and providing respirators.

Fresno County is now putting strong efforts into establishing multi-hazard resilience plans. And wildfire has been one of the targets in the plan. Several policies have been established to protect residents from potential life risks and property losses. Indeed, the implementation of wildfire mitigation actions is urgent and prioritized. However, mitigation strategies for wildfire smoke impacts are not included in the resilience framework. A lack of wildfire smoke mitigation actions not only happens in the resilience framework in Fresno County. Indeed, many counties include limited mitigation strategies for wildfire smoke exposure in resilience plans. In other words, there is a lack of protection of residents from wildfire smoke exposure provided by local governments.

Another aspect that needs to be considered when making a resilience plan is the existence of environmental injustice in communities. Communities with low-income, high unemployment rate, and minorities often endure a greater burden of wildfire smoke impacts. This is observed in Southern California during the 2007 wildfire event since one-third of the population experienced a lack of communication and information. The EPA has already defined environmental justice but clearly environmental injustice is still occurring. These disadvantaged communities should not be the ones suffering more severe consequences. Government agencies and policymakers need to properly consider them while making mitigation and resilience plans.

6. Conclusion and Recommendation

The overall objective of this project was to identify the public health impacts of wildfire smoke exposure and mitigation strategies within local government resilience plans in cities. Recommendations can be made to strengthen local government resilience plans by including inclusive and equitable measures to adapt and mitigate the impacts of wildfire smoke exposure. To reach this overall objective, the main research question for the project was: what impacts does wildfire smoke exposure have on public health in California and how should we use mitigation
strategies to reduce those impacts? To further understand how wildfire smoke affects public and how resilience plans can be used to mitigate and adapt to impacts, I also aimed to understand PM$_{2.5}$ in wildfire smoke and its impacts, identify correlations between wildfire smoke exposure and respiratory hospital admissions, analyze mitigation strategies assessable by individuals, determine city community characteristics and vulnerability to wildfire smoke exposure, and ultimately assess local government resilience plan of Fresno County in California, including the discussion of the role of environmental justice in wildfire mitigation.

6.1. Conclusion

My research uses a risk assessment framework by EPA to analyze wildfire smoke impacts in affected communities in California and local government resilience plan of Fresno County to determine if appropriate adaptation and mitigation strategies for wildfire smoke exposure are addressed. The risk assessment framework includes the steps of hazard identification, dose-response assessment, exposure assessment, risk characterization, and risk management. Climate change projection suggests wildfire events will be more frequent over the next few decades. Wildfire smoke exposure with PM$_{2.5}$ as well as carbon dioxide, ozone, carbon monoxide, and complex hydrocarbon has negative social impacts. It affects public health by increasing the risk of respiratory and cardiovascular illnesses including asthma, chronic obstructive pulmonary diseases and respiratory morbidity. Indeed, air pollution health impacts caused by wildfire smoke exposure are cumulative, and wildfire PM$_{2.5}$ exacerbates pre-existing health conditions.

The hazard identification examination of wildfire-specific PM$_{2.5}$ shows that it can lead up to a 10% increase in respiratory hospitalization admissions in comparison to ambient PM$_{2.5}$, which implies that wildfire-specific PM$_{2.5}$ is up to 10 times more harmful than PM$_{2.5}$ from other sources to human health. The dose-response assessment and exposure assessment of wildfire smoke impacts on public health have been observed through several case studies, using hospital admissions as the main indicator. The result shows that wildfire smoke can lead to at least 34% increase in hospital admissions (Southern California 2003). The maximum increase in hospital admission was observed in the 2007 San Diego wildfire, which is 112% increase in asthma visits in local hospitals. The dose-response shows that there was an average increase of 70µg/m$^3$ of PM$_{2.5}$ concentration during the wildfire period, leading to an average of 34% increase in asthma admissions. The
exposure assessment shows that the most vulnerable population were young children. Children experienced 136% to 243% increase in the number of visits for asthma in San Diego wildfires in 2007.

Overall, risk characterization of wildfire smoke exposure shows that wildfire smoke exposure is closely related to the increase in respiratory hospitalizations in affected communities. Therefore, adequate wildfire mitigation strategies are imperative. The risk management part in this project examines two mitigation methods that are accessible by the public, using air cleaners and using masks. The result shows that both methods are effective in reducing potential health risks, by approximately 60% in hospitalization reduction. However, air cleaners are expensive for some proportion of the population to afford. And only N95 can provide proper protection from wildfire smoke exposure. Ultimately, the resilience plan in Fresno County is analyzed. The plan includes actions to reduce wildfire impacts and risks on communities. However, it is lacking strength to adapt and mitigate the impact of wildfire smoke, and most importantly, provide concrete measures to prevent disproportionately impacting vulnerable and disadvantaged members of the community.

6.2. Recommendations

Given the risk assessment results, I have created recommendations to strengthen the protection of affected communities from wildfire smoke exposure, where wildfire smoke mitigation strategies are lacking in the resilience plans.

6.2.1. Identification of wildfire smoke

One of the objectives of the project is the identification of wildfire smoke hazards. There are already monitoring systems for regional PM$_{2.5}$ concentrations. In order to understand wildfire smoke risk, cities can identify a threshold of the PM$_{2.5}$ concentration in the atmosphere. It is beyond this concentration level that smoke can become dangerous to public health. And the threshold can be different among communities depending on the community characteristics. Identification of wildfire smoke exposure risks at an individual and community level determines what existing levels of risks are and to increase the understanding of vulnerabilities.
**Recommendation: Precisely identify vulnerable communities**

In order to identify wildfire smoke exposure risks, a recommendation is to create methods for identifying vulnerable communities when making county-level resilience plans by local government agencies. Within these methods, vulnerable communities can be identified and prioritized in implementing mitigation policies and strategies, analyzing effectiveness, and equitable practices. These methods should carefully identify the characteristics of the communities. For instance, communities with a higher proportion of elderly and children should be the priority in implementing mitigation strategies, such as distributing N95 masks and installing improved air condition systems. And the threshold of PM$_{2.5}$ concentration set in these communities should be lower than other communities, so that local governments can act early in protecting residents. And for the communities suffering from environmental injustice, local governments should include them in resilience plans and mitigation strategies. In addition, it is recommended to assess future risks by describing expected trends of wildfire smoke events that may influence smoke-related health outcomes and describe possible additional public health outcomes. And finally, it is critical to develop performance protocols in local communities for adaptation measures and monitoring the burden of vulnerable communities.

**Recommendations: Conduct further research about wildfire-specific PM$_{2.5}$**

The hazard identification and dose-response assessment in the risk assessment framework determines how wildfire smoke impacts public health. There have been several studies analyzing wildfire-specific PM$_{2.5}$. And the results show that wildfire-specific PM$_{2.5}$ is more toxic than PM$_{2.5}$ from other sources. One of the reasons is that wildfire smoke PM$_{2.5}$ can alter the composition of PM$_{2.5}$ in the local ecosystem. And the different compositions of PM$_{2.5}$ can cause a variety of health issues. However, there is a lack of study on how the change in PM$_{2.5}$ composition can potentially increase the public health risks. For instance, the relationship between the increase in organic carbon fraction in PM$_{2.5}$ during the smoke wave period and the increase in hospital admissions is not discovered. As a result, further studies are recommended to discover the relationship between the change of PM$_{2.5}$ composition and public health impacts.
6.2.2. Preparation to reduce wildfire smoke exposure

One of the objectives of wildfire smoke mitigation is preparing for the wildfire season and reducing smoke exposure. When preparing for the wildfire smoke season, cities can invest more in adaptation measures to prepare for an effective response given the city’s vulnerability to wildfire smoke exposure. Most of the wildfire-related actions in cities’ resilience plans focus on the impacts of wildfire itself. Only a few actions address the smoke exposure. It is essential that cities’ resilience plans include seasonal planning, where different strategies and actions are implemented throughout the year, and sector planning, where different sectors are prepared for wildfire smoke exposure. In other words, emergency management teams should prepare strategies for effective response plans during wildfire seasons. And when preparing for wildfire smoke exposure, strategies such as communication warnings, address risk perception, and prepare city sectors should be implemented. Within these preparation actions, environmental justice communities should be identified.

Recommendations: Improve access to and use of air filtration systems and masks

Within this recommendation, local government agencies should improve access to improved air conditioning systems with air filtration functions and air cleaners in vulnerable populations and address obstacles that prevent residents from using air filtration systems. For instance, children have been proved to be one of the most vulnerable populations suffering from wildfire smoke exposure. Local government agencies can encourage local public schools to install air filtration systems to protect children from wildfire smoke exposure. In addition to improving the access to air filtration systems, cities can prepare for the wildfire smoke exposure by protecting energy systems and expanding energy assurance. Local government agencies can achieve these goals by working with utilities to ensure air filtration systems such as air conditioners, air cleaners, and other essential services in vulnerable areas are protected.

Using masks is another effective way to protect residents from wildfire smoke exposure. Distribution of masks to vulnerable populations such as elderly and children can prevent them from PM$_{2.5}$ intake during wildfire events. Indeed, N95 masks should be delivered to vulnerable
populations in advance. And proper announcements and educational outreach in communities should be done to encourage residents to wear masks.

**Recommendations: Regulations to protect outdoor workers**

Cal OSHA has published standards limiting working conditions for outdoor workers during wildfire events. But the enforcement of the regulation is not strong. The main focus of Cal OSHA is to protect workers from negative health impacts in mining and tunneling industries. Employers in these industries should provide protections to their employees according to the regulation to get operation permissions from Cal OSHA annually. However, limited enforcement actions are designed for wildfire smoke impacts. In counties such as Fresno, a great number of workers in the communities are agricultural and industrial workers who need to work in the field. As a result, they are exposed directly to wildfire smoke. So, I recommend that Cal OSHA could work with local government agencies to protect these workers by making regulations more stringent. Any violation of the standard set by Cal OSHA should result in warnings, license suspension, and severe punishments of the company. Strict regulations supporting public health would ensure companies pay close attention to how they protect workers from wildfire smoke exposure.
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