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Understanding the Association between Wildfire Smoke PM2.5 Exposure and Mood Disorders in California from 2007-2018 a Case-Crossover Study

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Master of Public Health

Environmental Health and Epidemiology

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An abstract of

A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University

in partial fulfillment of the requirements for the degree of
Master of Public Health
in Environmental Health and Epidemiology

2023

Abstract:

Introduction: Climate change has emerged as the largest public health threat of the 21st century, causing areas like California to be exposed to more extreme heat days as well as severe droughts. These factors have led to an increase in number and intensity of wildfires in California releasing tons of smoke and PM2.5. We aimed to understand the association between wildfire smoke PM2.5 exposure and an increase of Emergency Department (ED) visits for mood disorder from 2007-2018.

Methods: This study was a case crossover study where each case had 3-4 controls. We looked at their exposure to wildfire smoke PM2.5 level 48 prior to their ED visit based on the zip code we had on their medical record. We used ICD9 and ICD10 codes to determine if a patient came in for a mood disorder. We specifically focused on wildfire season (May-October) and those who came to the ED for a primary mood disorder.

Results: During wildfire season, those who came to the ED and were diagnosed with a primary mood disorder had 1.02 times higher odds of being exposed to between 0.69-1.39 μm/m3(25th-50th quartile) compared to the odds of coming to the ED for a primary mood disorder among those exposed to no wildfire smoke (p= 0.001).

Conclusion: Our findings seem to suggest that wildfire smoke PM2.5 exposure's association with mood disorders might be more physiological than psychological since we saw increased odds at PM2.5 levels that are not noticeable to the human eye or nose.

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Literature Review:

Introduction to PM2.5 and wildfire smoke:

Outdoor air pollution consists of multiple different components including natural components like mold, pollen, spores, and dust, as well as human caused pollutants (*Outdoor Air Quality | US EPA*, n.d.). The Environmental Protection Agency (EPA) has created a category called criteria air pollutants which consists of six of the most common pollutants in the air, one of which is particulate matter (PM). Particulate matter (PM), sometimes called particle pollution, is a mixture of solid particles and liquid droplets including but not limited to PM10 and PM2.5(*Particulate Matter (PM) Basics | US EPA*, n.d.). PM10, and PM2.5 are classifications of PM, where PM 10 is any particulate matter that is less than or equal to 10 micrometers(µm), and PM2.5 is any particulate matter that are less than or equal to 2.5 µm (*Particulate Matter (PM) Basics | US EPA*, n.d.). Examples of PM10 include dust and pollen, PM2.5 is typically produced from combustion like vehicle exhaust, factories, and wildfires.

While there are many sources that contribute to PM2.5 in outdoor air pollution, over the years wildfire smoke is becoming a more significant source of PM2.5. While there is a fair amount of literature regarding wildfire smoke and cardiovascular diseases, there is much less regarding wildfire smoke and mental health. This literature review aims to summarize the findings from prior publications. Due to the lack of papers relevant for this literature review, I will begin by reviewing papers on Air pollution and mental health and then look more specifically on wildfire smoke and mental health outcomes. I will focus the most on findings from papers regarding mood disorders including depression, and bipolar disorder among other mood disorders.

Air Pollution and Mental Health:

Borroni et al, did a systematic review and meta-analysis regarding air pollution exposure and depression and Buoli et al did a literature review regarding studies about an association between psychiatric disorder and air pollution (Borroni et al., 2022; Buoli et al., 2018). I will be discussing findings from both reviews as well findings from specific studies that were part of their reviews. Among the papers reviewed by Borroni, 21 studies looked at short term effects of air pollution exposure, while 16 looked at long term air pollution exposure. According to their meta-analysis, Borroni et al found that a 10 $\mu g/m^3$ increase in both PM10 and PM2.5 were associated with a 1% increase in risk of depression (Borroni et al., 2022). In a case crossover study done in Canada across multiple cities, they found that males exposed to PM2.5 was associated with increased risk of depression one day after exposure (Szyszkowicz et al., 2016). In another study looking at PM10 and PM2.5 in multiple cities in China found a positive percent change in depression admission for an interquartile range increase in PM10 and PM2.5 for 0–6-day lag (Wang et al., 2018). In a time series study done in California from 2005-2013, Nguyen et al found that at lag 0 short term exposure to PM2.5 per 10µg/m increase was associated with all mental health outcomes. However, when looking at depression and mood disorders specifically the results were not statically significant (Nguyen et al., 2021). Cho et al did a study where they looked at short term ambient air pollution levels and the risk of a depressive episode using ED data in Seoul among disease subpopulations which were cardiovascular disease (CVD), ischemic heart disease, chronic obtrusive pulmonary disease (COPD), asthma, and prior depressive episodes. They found that when looking at those who had of the diseases above, there was a significant association between sulfur oxide (SO_2) and ozone (O_3) but not PM10. However, SO_2,

O_3, and PM10 were positively associated when looking at any of the five subpopulations (Cho et al., 2014).

Wildfire Smoke and Mental Health:

While there is some literature regarding wildfire smoke exposure and mental health, there is substantially less literature. Reid et al did a critical review regarding the health impacts of wildfire smoke exposure, while Eisenman and Galway did a scoping review regarding wildfire smoke exposure and mental health (Eisenman & Galway, 2022; Reid et al., 2016). I will be summarizing their findings as well as highlighting some of the papers that were a part of their review. Reid et al, found that overall, the studies that looked at wildfire smoke and mental health outcomes did not find an association between them. One of the studies, by Moore et al, was a time series study that looked at physician visits for various diseases in British Columbia, they found that while there was an increase in the number of visits for respiratory diseases, they did not see any effects between wildfire smoke exposure and mental health visits (Moore et al., 2006). Both Reid and Eisenman noted that quantitative studies are limited due to their methodologies and therefore one of the reasons there are inconsistent findings. They do note that studies looking at wildfire smoke exposure and mental health outcomes are in their infancy, and therefore more research is needed (Eisenman & Galway, 2022; Reid et al., 2016). Eisenman and Galway do also note that qualitative research provided a richer and more nuanced understanding of the impact wildfire smoke exposure has on mental health while avoiding the limitations and stigmas of pathological framework (Eisenman & Galway, 2022).

Conclusions:

Air pollution exposure, especially wildfire smoke exposure, and its effect on mental health is in its infancy. More studies are needed to understand the mental impacts of wildfire smoke exposure so that we can best support vulnerable populations. With climate change increasing the frequency and intensity of wildfires we are expected to see an increase in wildfire smoke PM2.5 exposure. While the meta-analysis Borroni et al did found that a 10 $\mu g/m^3$ increase in PM was associated with a 1% increase in risk of depression, there were also studies that did not find statistically significant associations between air pollution and depression. More research is needed to best understand any association between wildfire smoke exposure and mental health. This includes having better measures of wildfire smoke exposure, as well as diagnostic methodologies.

Thesis

Introduction

Climate change has emerged as the largest public health threat of the 21st century (*Climate Change and Health*, n.d.). According to the World Health Organization (WHO) outdoor air pollution is responsible for 4.2 million premature deaths per year (*Data Review: How Many People Die from Air Pollution? - Our World in Data*, n.d.). In the contiguous United States, outdoor air pollution is responsible for five to ten percent of the annual premature mortality (Dedoussi et al., 2020). Among pollutants in outdoor air pollution, particulate matter specifically PM 2.5 is a big concern for the threat is poses to health outcomes. PM 2.5 is any particulate matter that is smaller than 2.5 microns in diameter and is produced during combustion. Examples include vehicle emissions, power plants, and wildfire smoke. California is one of the states that has been most affected by wildfires. California is a unique state due to the fact that over one third of the state is forest land. Most of it is designated protected land by either the federal or state government. Given the physical landscape as well as the lack of rain/moisture during the summer, California has always been a hotspot for wildfires. However, incidence of wildfires in California as well as the total acres burned has trended upwards since 1999 (Buechi et al., 2018). No statistic shows that better than the fact that the seven largest wildfires in California's history have happened in the last five years (2018-2022) (*Top20_acres*, n.d.). In fact if you look at the average wildfire smoke PM 2.5 in California from 2007-2012 compared to 2013-2018, we can clearly see higher levels of wildfire smoke PM 2.5 in 2013-2018 (Figure 1).

History of Wildfire Suppression

To understand the effect of wildfire smoke, we must understand the roles wildfires play, as well as the social and policy choices that have led to the sharp increase in wildfires in California. While we often think wildfires are harmful due to all the destruction they cause, they are important from an ecological standpoint. Wildfires help ecosystems in a plethora of ways. They help burn underbrush on the forest floors, allowing the soil to be exposed to sunlight and a better allocation of nutrients to trees. Secondly, wildfires allow for new grasses and plants to grow producing food and shelter for small animals while also killing pests that can harm the ecosystem. Lastly, many of the trees in California are reliant on wildfires to help them spread their seeds. Trees like the giant sequoias rely on wildfires to dry their cones, which in turn opens the cones releasing seeds to help grow more giant sequoias (*Fire and the Giant Sequoia*, n.d.). In fact, Native Americans historically used fires as a method to improve agriculture and their hunting grounds (Jaffe et al., 2020). Despite, these benefits, there has been a conscious effort of fire suppression in California, and the greater United States in that last 100 years.

In the 1800s forests were being taken down for timber using a slash and burn technique which burns land to create space for production (Dombeck et al., 2004). Coupled with droughts these techniques led to one of the most fatal fires in Wisconsin where more than 1200 people died (Estep, n.d.). In 1910, we also had the Great Fires, which burned across Idaho, Montana, and Washington. These fires were made worse by the drought the area had the year prior, and high gusty winds helped spread the fire faster than it could be contained (Pyne, 2001). These large wildfires, and the creation of the U.S Forest Service (USFS) in 1905, led to changes in policies and how we viewed wildfires as a society. Instead of seeing wildfires as an aid, USFS decided that fire suppression would be its primary focus creating a Smokey the bear, and the "Only you can prevent wildfires" slogan leading to a societal wide view that all wildfires are bad

(Dombeck et al., 2004). This has allowed small grasses and weeds to grow rampantly in these forests harming ecosystems, and just as importantly creating more fuel for a wildfire to burn.

With forests, and land building fuel, and the effect of climate change creating more extreme heat days, as well as more severe droughts, California has become the hot spot for wildfires. Ford et al noted that while overall PM 2.5 exposure will decrease due to less anthropogenic emission, there will be an increase in fire related PM2.5 exposure (Ford et al., 2020). These wildfires are dangerous as they can both destroy people's homes and community, but people are also exposed to elevated levels of PM 2.5. While it is important to create policies to prevent large scale wildfires, we must also understand the health impacts of wildfire smoke exposure.

Health Effects due to wildfire smoke exposure:

Wildfire smoke discharge various compounds including carbon dioxide (CO_2), nitrogen oxide (NOx), Carbon Monoxide (CO), methane (CH_4), and volatile organic compounds (VOC's) which help form PM2.5. While the largest emission from these wildfires is CO_2, primary PM2.5 makes up about 8% of emissions (Jaffe et al., 2020). This smoke contributes to PM 2.5 exposure in California, especially during wildfire season. However, climate change is expected to increase the duration of fire season and the rate of wildfires, not just in California, but all North America (Sun et al., 2019). While there has been limited research on the biological mechanism of wildfire smoke, and cardiovascular health effects, Chen et al has created a possible pathway based on prior literature. There are two main forms of exposure, inhalation and dermal exposure. This exposure can lead to autonomic nervous system imbalance, oxidative stress, and systemic inflammation which leads to increased heart rate, poorer coronary flow, and increased reactive oxygen species (ROS) which leads to various cardiovascular events (Chen et al., 2021). In a literature review of the current research regarding wildfire smoke and cardiovascular events, Chen et al had some interesting findings. Of the 38 studies looking at cardiovascular morbidity, 25 found a positive association between wildfire smoke exposure and a higher need of care for CVD. 10 papers looked at cardiovascular mortality, and 8 of those papers had a positive association between wildfire smoke and mortality (Chen et al., 2021). Among all the 48 epidemiology papers, 21 looked at wildfire smoke PM2.5. Of those 21 studies, 15 found a positive association between PM2.5 exposure and various cardiovascular events. This further highlights the strong evidence of the association between wildfire smoke PM2.5 exposure and its effect on cardiovascular events.

While there is a fair amount of literature regarding the association between wildfire smoke exposure and cardiovascular events, there are less and more inconsistent results when it comes to wildfire smoke and mental health. Similarly, to cardiovascular disease, there is not a commonly accepted biological mechanism for wildfire smoke and mental health. However, Buoli et al does a review of air pollution and mental health, and suggested a biological mechanism, where acute inhalation of PM2.5 leads to inflammation and oxidative stress leading to neurotoxicity and a worsening of existing mental conditions (Buoli et al., 2018). Another scoping review, that looked at wildfire smoke and mental health, looked at pathways on the social ecological model, and noted that wildfire smoke exposure, can affect people on across all levels (individuals, social, living and working, and ecological) (Eisenman & Galway, 2022). From the scoping review done by Eisenman & Galway, the quantitative research studies were inconsistent due to various study designs and limitations from the studies including having a non-random sample, and not differentiating between rural and urban areas (Eisenman & Galway, 2022).

To better understand the burden of wildfire smoke exposure, my research looks to understand the effect of wildfire smoke PM2.5 exposure on mood disorders like depression and bipolar disorder. This study will look at individuals' acute exposure to wildfire smoke PM2.5, and visits to the emergency department (ED) in California where they were diagnosed with a mood disorder from 2007-2018. Patient's exposure was determined based on the zip code they provided for their home, and zip code level wildfire smoke PM2.5. Due to the temporal scope, looking at anyone who came to the ED and was diagnosed with a mood disorder from 2007-2018, and the spatial scope, looking at all of California, of this study, we believe we can have a clearer understanding of acute wildfire smoke exposure and mood disorders among adults in California.

Methods:

For this study I used a wildfire smoke PM2.5 model, created by Dr. Liu and his research team. This model used a combination of preexisting models like the Community Multiscale Air Quality Modeling System (CMAQ), various satellite remote sensing products, land cover and land use information, reanalysis meteorology, and ground observations from both standard and low-cost sensors like PurpleAir. This allowed the team to create a multistage chemical transport model (CTM) to estimate daily smoke PM2.5 concentration in the contiguous United States at a 1km spatial resolution by utilizing the high spatial and temporal resolution of the model. This model was created with the purpose of investigating the long-term impacts of wildfire on air quality across the United States of America. After getting the data for a 1 km resolution, they created an average daily smoke PM2.5 count on a zip code level by aggregating the data and averaging the daily smoke count.

For our health dataset, we got data on every patient who came to the ED in California and was diagnosed with a mood disorder from 2007-2018. We created a variable called MOOD1, which was how we distinguished patients whose primary diagnosis was a mood disorder, vs those who were diagnosed with a mood disorder but not as their primary problem/issue. Mood disorders were classified based on the International Classification of Disease (ICD) 9 and 10 codes. The codes for a mood disorder are ICD9 codes: 296, 300.4, 301.10, 301.12, 301.13, and ICD10 codes: F30-F39. To create our cohort, we only included those whose home zip code was a California zip code, since we are measuring wildfire smoke PM2.5 in California. We also excluded any patients who put a PO box zip code as their zip code as we cannot gauge their exposure since, we do not know how close they live in relation to the PO box. Patients who had a PO box zip code accounted for less than 2% of all cases. Once all non-CA and PO box patients were removed, we were left with 4,793,826 cases total. Of those cases, 674,397 had a primary diagnosis of a mood disorder (Table 1).

For our study we decided to do a case-crossover study, where each patient served as their own control. A case-crossover study is beneficial because it naturally controls for a lot of demographics for each case including age, sex, and preexisting conditions. For our controls, we matched the case on the same day of the week, and month. This meant that if a case went to the ED on a Tuesday in March 2008, they would have a control for every Tuesday in March 2008 creating 3-4 controls per case. We chose to pick our control based on the day and the month, because it will help control seasonality, as well as the acute temporal relationship between wildfire smoke PM2.5 and mood disorders. Case-crossover study also allows us to study individuals rather than days as the unit of observation while using our wildfire smoke data (Jaakkola, 2003).

Wildfire smoke was calculated by subtracting the non-smoke PM2.5 from total PM2.5. Since the model is a prediction of wildfire smoke PM2.5 there was a certain amount of random error which led to days where wildfire smoke PM2.5 was a negative value. Those values were changed to zero since it is impossible to have days where wildfire smoke PM2.5 is negative. Our wildfire smoke dataset is a right skewed dataset since wildfire smoke PM2.5 levels are an event-based exposure and on days and area where there is a wildfire we see the wildfire smoke PM2.5 levels drastically increase (Figure 2). Overall, about half of all the days in our dataset from 2007-2018 had no wildfire smoke at the zip code level. To adjust for this, we decided to focus our case crossover cohort to wildfire season in California. While there is no official timeline for wildfire season, and climate change continues to extend wildfire season, we decided to make May-October wildfire season. This was decided through looking at wildfire smoke PM2.5 levels across years and finding the most common months where there was elevated wildfire smoke. By focusing only during wildfire season, we see the days with no wildfire smoke PM2.5 decrease from about 65% to 35%. Table 2 shows the summary statistics for the wildfire season cohort. We decided to look at acute wildfire smoke PM2.5 exposure among all patients who came to the ED and were diagnosed with a mood disorder as well as those whose primary diagnosis at the ED was a mood disorder. This is due to the fact of how health issues are coded and diagnosed in an ED setting. A primary diagnosis is the most pressing and relevant health issue affecting the patient. Once we got past the primary diagnosis it is hard to understand how high of a concern a mood disorder diagnosis was. As a result, we looked at the impact wildfire smoke PM 2.5 has on mood disorders overall, and among those whose main health diagnosis in the ED was a mood disorder.

Outside of the wildfire smoke and patient dataset, we also wanted information regarding average temperature, and relative humidity. We used a dataset from NASA called the Daily Surface Weather and Climatological Summaries (DAYMET) which had average daily temperature and vapor pressure on a zip code level in California. Using the average temperature, we were able to calculate the dew point using the following formula $\left(6.112 \cdot \left(e^{\left(\frac{(17.62 \cdot tmean)}{(243.12+tmean)}\right)}\right)\right)$. We then divided the vapor pressure by the dew point and divided it by 100 to get the relative humidity (Lawrence, 2005).

When creating out models, we decided to look at how different factors might affect our models. First, we created lag variables for the wildfire smoke variable ranging from day 0 (wildfire smoke the day a patient came to the ED) to lag 5, (wildfire smoke 5 days prior to the patients ED visit). Second, we decided to look at some of our confounding variables effect on the model with different degrees of freedom as a natural spline; these included day of year (4-6), temperature (4-6), and relative humidity (4-6). This analysis allowed us to ensure we had the best fitting model to show any association between wildfire smoke and mood disorders.

Due to the size of the dataset, (over 20 million rows overall, and 10 million rows during wildfire season), all the code was run using a high-powered computer (HPC). All the coding was written and executed using R 4.0.2 and R studio.

Results:

Wildfire smoke was originally a continuous variable, but we decided to make it categorical based on any exposure as well as quantiles. We also viewed wildfire smoke exposure on a 0-5 day lag and average where day 0 meant that someone was exposed to wildfire smoke and came to the ED that same day. The lag helps show how exposure over multiple days can lead to changes in mood disorder visits in the ED. Furthermore, it shows the potential lag between exposure and when we see the effects. We decided to have two different lags. The first is 0-5 day lag where the lag day is just what the wildfire smoke PM2.5 was that day prior (i.e. lag 1 is the wildfire smoke PM2.5 1 day prior to the ED visit). The second is average wildfire smoke PM 2.5 (i.e., 48-hour average is the average wildfire smoke between the day the patient came to the ED (day 0) and the day prior (lag 1). For all our models we looked at the average wildfire smoke exposure in the 48 hours (about 2 days) prior to diagnosis. (day 0 and lag 1). First, we made wildfire smoke PM2.5 a binary variable, where if there was any wildfire smoke in the air, it would be categorized as a 1 and days with no wildfire smoke it would be a 0. During wildfire season, the odds of going to the ED for a primary mood disorder among those who were exposed to any wildfire smoke was 1.013 times the odds of going to the ED for a mood disorder among those who were not exposed to any wildfire smoke ($p = 0.01$). Women were more likely to go to the ED for a primary mood disorder diagnosis after being exposed to any wildfire smoke during wildfire season ($OR = 1.017$, $p = 0.01$) compared to men ($OR = 1.008$, $p = 0.2$) controlling for temperature, relative humidity, day of year, and federal holidays. For average temperature, relative humidity, and day of the year variables we ran a natural spline with 5,5, and 4 degrees of freedom respectively to create a better fitting model. While these findings are relevant, they do not tell us a lot since we don't know how much wildfire smoke exposure is needed to affect mood disorders.

To get a better understanding we decided to switch to quantiles. However, since more than 25% of all the days during wildfire season had no wildfire smoke, we decided to look at the quantiles of all non-zero wildfire smoke days compared to days where there was no wildfire smoke PM2.5. We first looked at all patients who came to the ED and were diagnosed with a mood disorder but could not find any statistically significant results (Figure 3). We then decided to look at only those whose primary diagnosis was for a mood disorder. During wildfire season, those who came to the ED for a primary mood disorder had 1.02 times higher odds of being exposed to between 0.69-1.36 mm/m^3 compared to the odds of coming to the ED for a primary mood disorder among those exposed to no wildfire smoke (p= 0.001). Even when stratifying by gender, we see that among women and men who came to the ED for a primary mood disorder both had 1.02 times greater odds of being exposed to 0.69-1.37 and 0.68-1.36 mm/m^3 respectively compared to the odds of coming to the ED for a primary mood disorder among those exposed to no wildfire smoke (p=0.007, 0.03 respectively). The other quartiles did show increased odds ratio of coming to the ED for a primary mood disorder compared to those who were not exposed to any wildfire smoke PM2.5 but the results were not statistically significant (Figure 4).

Discussion:

The effects of wildfire smoke exposure and mental health is a relatively new research topic with more and more research coming out every day. Our study looked at how acute wildfire smoke exposure could affect mood disorders and the number of mood disorder cases in the ED. Overall, we found that wildfire smoke exposure increases the odds of coming to the ED for a primary mood disorder. When looking at non-zero quantile levels, only the 25^{th}-50^{th} percentile showed an increased odds of ED visits both overall and stratified by males and females compared to those who were not exposed to any wildfire smoke. This seems to suggest that the association between wildfire smoke PM2.5 exposure might be more physiological than psychological, since the days where we saw increased odds were on days when wildfire smoke probably was not too visible. Another hypothesis for why we only saw increased odds of ED visits in the 25^{th}-50^{th} percentile, is due to the fact that when there is higher exposure to wildfire smoke, people most likely will be spending more time indoors where they have better ventilation limiting their exposure to wildfire smoke. Furthermore, people might be evacuating when wildfire smoke gets too high which could also limit their exposure. When wildfire smoke PM2.5 levels are on average between 0.68-1.35 mm/m^3 over the last 48 hours, people aren't able to really see or feel its impact. This means that people are more likely to spend more time outdoors inhaling wildfire smoke. Other quartile also showed increased odds ratio for all the other quartile but these results were not statically significant. One of the reasons this might be the case is because of how wildfire smoke data is right skewed meaning that there are only a few days with very intense wildfire smoke.

This study had a few limitations. The first is that we were only looking at emergency department visits which means we are looking at some of the most extreme mood disorder cases. Many people experience mood disorders in more minor forms that we are not accounting for in this study. Secondly, we could not measure prior mental health history, so we are unsure if the people coming to the ED are people with a history of mood disorders or other mental health struggles, or people who are experiencing mood disorders for the first time. Given the increase in the number and severity of wildfires in California, as well as the increase in dry days due to climate change, it is imperative we understand the health impact wildfire smoke exposure has on human health especially their mental health. Future studies should be done to address these gaps to better understand both the physiological and psychological impact wildfire smoke PM2.5 has on mood disorders and mental health overall both in an ED setting, but also among those who deal with mood disorders but don’t feel the need to come to the ED.

Appendix:

Table 1: Summary Statistics of all cases and primary cases during from 2007-2018

	All Cases (n= 4793826)	All Primary Cases(n=674397)
Biological **Sex**	**n(%)**	**n(%)**
Male	1795062 (37.45)	317850 (47.13)
Female	2998574 (62.55)	356497 (52.86)
Unknown	190 (0)	50 (0.01)
Age		
18-35	1127667 (23.52)	284306 (42.16)
36-65	2447691 (51.06)	338671 (50.22)
66+	1218468 (25.42)	51420 (7.62)
Race		
White	3439849 (71.76)	458795 (68.03)
Black	519924 (10.85)	82587 (12.25)
AI/AN	25817 (0.54)	2999 (0.44)
Asian/PI	178343 (3.72)	30987 (4.59)
Other	579480 (12.09)	84826 (12.58)
Unknown	504113 (10.52)	14203 (2.11)
Season		
Autumn	1227389 (25.6)	169146 (25.08)
Spring	1183844 (24.7)	170906 (25.34)
Summer	1214502 (25.33)	174602 (25.89)
Winter	1168091 (24.37)	159743 (23.69)
Primary Mood diagnosis		
Yes	674397 (14.07)	
No	4119429 (85.93)	

Table 2: Summary Statistics of all cases and primary cases during wildfire season (May-October) 2007-2018

	All Cases Wildfire Season (n =2,438,928)	All Primary Cases (n=347,384)
Biological Sex	**n(%)**	**n(%)**
Male	912567 (37.42)	163463 (47.07)

Female	1526263 (62.58)		183797 (52.92)
Unknown	98 (0)		24 (0.01)
Age			
18-35	582240 (23.87)		146328 (42.13)
36-65	1255539 (51.48)		174427 (50.23)
66+	601149 (24.65)		26529 (7.64)
Race			
White	1747823 (71.66)		236345 (68.06)
Black	265225 (10.87)		42390 (12.21)
AI/AN	13363 (0.55)		1544 (0.44)
Asian/PI	89964 (3.69)		15671 (4.51)
Other	296941 (12.18)		44137 (12.71)
Unknown	25612 (1.05)		7197 (2.07)
Season			
Autumn	822657 (33.73)		115021 (33.12)
Spring	401751 (16.47)		57661 (16.6)
Summer	1214502 (49.8)		174602 (50.28)
Primary Mood diagnosis			
Yes	347284 (14.24)		
No	2091644 (85.76)		

Figure 1: Average Wildfire smoke 2007-2012 vs 20013-2018

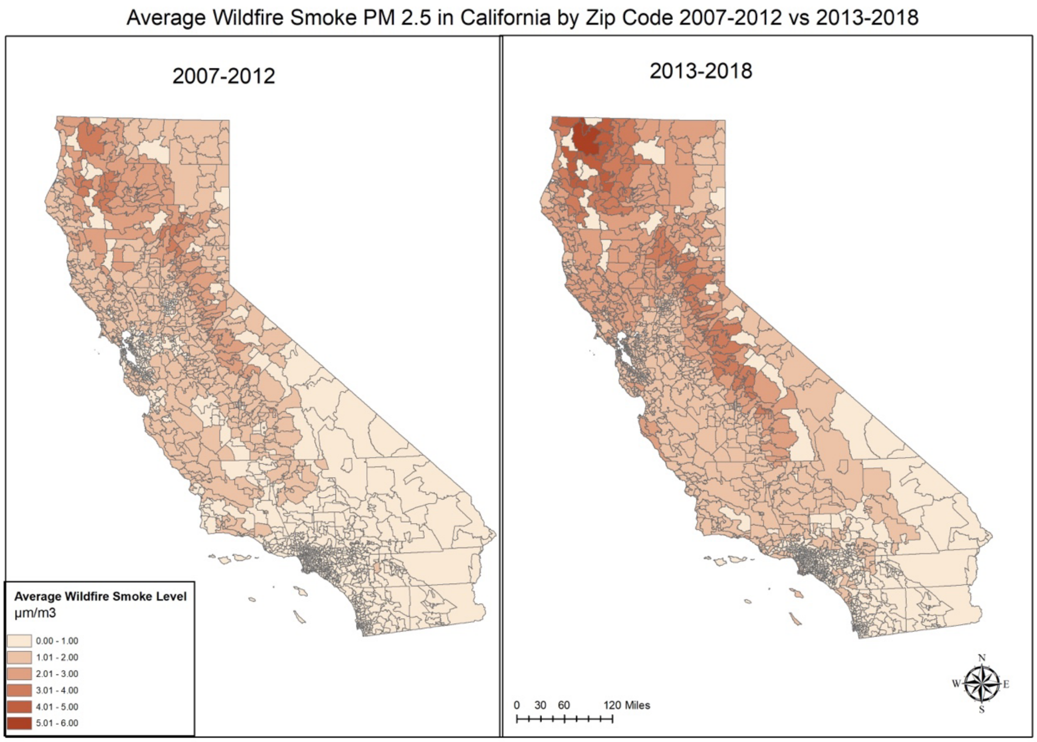

Figure 2: Wildfire Smoke PM 2.5 Statistics (µm/m³)

	25th	50th	Mean	75th	Max
Daily wildfire					
Entire Year	0	0	1.11	1.33	257.31
Wildfire Season	0	0.49	0.45	0.86	168.57
48 hr Average					
Entire Year	0	0.02	1.11	1.27	250.74
Wildfire Season	0	0.66	1.45	1.81	137.71

Figure 3: Wildfire Smoke's effect on Mental Health During Wildfire Season Results:

	OR	CI	P value
Any wildfire smoke exposure	1.01292	1.00311-1.02283	0.00974
Females Any wildfire smoke	1.01716	1.00362-1.03088	0.01281
Males Any wildfire smoke	1.00814	0.99395-1.02253	0.26239
Quantile Exposure a			

0.00-0.00	--	--	--
0.001-0.702	1.001	0.996-1.005	0.82037
0.703-1.398	1.004	0.999-1.009	0.0324
1.399-2.482	1.006	1.001-1.011	
2.482+	1.006	0.999-1.011	0.0123

Figure 4: Primary Mood Disorders during Wildfire Season

Primary Mood WFSZN	OR	CI	P value
All Cases			
0.00-0.00	--	--	--
0.0001-0.68592	1.0073	0.9947-1.0199	0.2564
0.68593-1.36445	1.0208	1.0080-1.0338	0.0014
1.36446-2.39641	1.0124	0.9990-1.0260	0.0698
2.39641+	1.0112	0.9964-1.0262	0.1383
Females			
0.00-0.00	--	--	--
0.0001 - 0.68891	1.0134	0.9962-1.031	0.1274
0.68892-1.37205	1.024	1.0064-1.0419	0.0074
1.37206-2.41053	1.0177	0.9992-1.0364	0.0609
2.41054+	1.0112	0.9909-1.0364	0.2802
Males			
0.00-0.00	--	--	--
0.0001 - 0.68243	0.9996	0.9815-1.018	0.9667
0.68244-1.35584	1.02	1.0020-1.0395	0.0294
1.35585-2.38079	1.0021	0.9828-1.0218	0.8324
2.38079+	1.0125	0.9911-1.0344	0.2533

Citations:

Borroni, E., Pesatori, A. C., Bollati, V., Buoli, M., & Carugno, M. (2022). Air pollution exposure and depression: A comprehensive updated systematic review and meta-analysis. *Environmental Pollution*, *292*, 118245. https://doi.org/10.1016/J.ENVPOL.2021.118245

Buechi, H., Market, E., Cameron, D., & Nature, T. (2018). *Wildfire-Brief*. 1–9.

Buoli, M., Grassi, S., Caldiroli, A., Carnevali, G. S., Mucci, F., Iodice, S., Cantone, L., Pergoli, L., & Bollati, V. (2018). Is there a link between air pollution and mental disorders? *Environment International*, *118*, 154–168. https://doi.org/10.1016/J.ENVINT.2018.05.044

Chen, H., Samet, J. M., Bromberg, P. A., & Tong, H. (2021). Cardiovascular health impacts of wildfire smoke exposure. *Particle and Fibre Toxicology 2021 18:1*, *18*(1), 1–22. https://doi.org/10.1186/S12989-020-00394-8

Cho, J., Choi, Y. J., Suh, M., Sohn, J., Kim, H., Cho, S. K., Ha, K. H., Kim, C., & Shin, D. C. (2014). Air pollution as a risk factor for depressive episode in patients with cardiovascular disease, diabetes mellitus, or asthma. *Journal of Affective Disorders*, *157*, 45–51. https://doi.org/10.1016/J.JAD.2014.01.002

Climate change and health. (n.d.). Retrieved February 4, 2023, from https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

Data Review: How many people die from air pollution? - Our World in Data. (n.d.). Retrieved February 4, 2023, from https://ourworldindata.org/data-review-air-pollution-deaths

Dedoussi, I. C., Eastham, S. D., Monier, E., & Barrett, S. R. H. (2020). Premature mortality related to United States cross-state air pollution. *Nature 2020 578:7794*, *578*(7794), 261–265. https://doi.org/10.1038/s41586-020-1983-8

Dombeck, M. P., Williams, J. E., & Wood, C. A. (2004). Wildfire Policy and Public Lands: Integrating Scientific Understanding with Social Concerns across Landscapes. *Conservation Biology*, *18*(4), 883–889. https://doi.org/10.1111/J.1523-1739.2004.00491.X

Eisenman, D. P., & Galway, L. P. (2022). The mental health and well-being effects of wildfire smoke: a scoping review. *BMC Public Health*, *22*(1), 1–17. https://doi.org/10.1186/S12889-022-14662-Z/FIGURES/2

Estep, K. (n.d.). *The Peshtigo Fire*. Retrieved February 10, 2023, from https://www.weather.gov/grb/peshtigofire

Fire and the Giant Sequoia. (n.d.). Retrieved February 10, 2023, from http://www.150.parks.ca.gov/?page_id=27588

Ford, B., Val Martin, M., Zelasky, S. E., Fischer, E. V., Anenberg, S. C., Heald, L., & Pierce, J. R. (2020). FUTURE FIRE IMPACTS ON SMOKE CONCENTRATIONS, VISIBILITY, AND HEALTH IN THE CONTIGUOUS UNITED STATES. *Wildfires: Air Quality Impacts and Smoke Exposure*, 212–254. https://doi.org/10.1029/2018GH000144

Jaakkola, J. J. K. (2003). Case-crossover design in air pollution epidemiology. *European Respiratory Journal*, *21*(40 suppl), 81s–85s. https://doi.org/10.1183/09031936.03.00402703

Jaffe, D. A., O'Neill, S. M., Larkin, N. K., Holder, A. L., Peterson, D. L., Halofsky, J. E., & Rappold, A. G. (2020). Wildfire and prescribed burning impacts on air quality in the United

States. *Journal of the Air & Waste Management Association (1995)*, *70*(6), 583. https://doi.org/10.1080/10962247.2020.1749731

Lawrence, M. G. (2005). The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications. *Bulletin of the American Meteorological Society*, *86*(2), 225–234. https://doi.org/10.1175/BAMS-86-2-225

Moore, D., Copes, R., Fisk, R., Joy, R., Chan, K., & Brauer, M. (2006). Population Health Effects of Air Quality Changes Due to Forest Fires in British Columbia in 2003: Estimates from Physician-visit Billing Data. *Canadian Journal of Public Health = Revue Canadienne de Santé Publique*, *97*(2), 105. https://doi.org/10.1007/BF03405325

Nguyen, A. M., Malig, B. J., & Basu, R. (2021). The association between ozone and fine particles and mental health-related emergency department visits in California, 2005–2013. *PLOS ONE*, *16*(4), e0249675. https://doi.org/10.1371/JOURNAL.PONE.0249675

Outdoor Air Quality | US EPA. (n.d.). Retrieved February 19, 2023, from https://www.epa.gov/report-environment/outdoor-air-quality

Particulate Matter (PM) Basics | US EPA. (n.d.). Retrieved February 19, 2023, from https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, *124*(9), 1334–1343. https://doi.org/10.1289/EHP.1409277

Sun, Q., Miao, C., Hanel, M., Borthwick, A. G. L., Duan, Q., Ji, D., & Li, H. (2019). Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environment International*, *128*, 125–136. https://doi.org/10.1016/J.ENVINT.2019.04.025

Szyszkowicz, M., Kousha, T., Kingsbury, M., & Colman, I. (2016). Air Pollution and Emergency Department Visits for Depression: A Multicity Case-Crossover Study. *Environmental Health Insights*, *10*. https://doi.org/10.4137/EHI.S40493/ASSET/IMAGES/LARGE/10.4137_EHI.S40493-FIG2.JPEG

top20_acres. (n.d.).

Wang, F., Liu, H., Li, H., Liu, J., Guo, X., Yuan, J., Hu, Y., Wang, J., & Lu, L. (2018). Ambient concentrations of particulate matter and hospitalization for depression in 26 Chinese cities: A case-crossover study. *Environment International*, *114*, 115–122. https://doi.org/10.1016/J.ENVINT.2018.02.012