Impact of Wildfire Smoke on PM2.5, CO, NO2, and SO2 Levels

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AUTHOR BIO

Serena Tan is a 12th grader in the International Baccalaureate program at Pacific Academy in British Columbia, Canada. She is interested in mathematics and the sciences, and often participates in math competitions. As her region is often affected by wildfires, she has been inspired to explore the potential consequences of fires on air quality.

ABSTRACT

Air pollution can negatively impact public and individual health, as well as the environment. This paper investigates the impact of wildfires on levels of different air pollutants in order to determine whether focusing on reducing wildfires can be an efficient way to reduce specific pollutants. By plotting the number of acres burning in wildfires along with the overall concentration of particulate matter less than 2.5 microns in diameter (PM2.5), carbon monoxide (CO), nitrogen dioxide (NO2), and sulfur dioxide (SO2) during a period of time in California, this paper estimates the contribution of wildfire smoke to the level of each pollutant. The results show that PM2.5 levels were the most heavily impacted by wildfires out of the four pollutants studied, and therefore actions to reduce the size and quantity of wildfires can be helpful to reduce the damage done by PM2.5 pollution. However, CO, NO2, and SO2 levels, while they may be correlated with fire size, are likely more strongly influenced by other factors. To minimize the harmful effects of these three pollutants, it may be more effective to focus on investigating other sources of CO, NO2, and SO2, such as the burning of fossil fuels in industrial machinery and motor vehicles.

Keywords: Air quality, Air pollution, Wildfire, Particulate matter, Carbon monoxide, Nitrogen dioxide, Sulfur dioxide, PM2.5

INTRODUCTION

Air pollution poses a significant risk to human health. In 2019, the WHO estimated that the effects of ambient air pollution led to approximately 4.2 million premature deaths worldwide every year (World Health Organization, 2022). Air pollutants have been found in numerous studies to affect the respiratory system in both high and low concentrations; increased exposure to pollutants like nitrogen oxides, sulfur dioxide, and certain heavy metals can lead to symptoms such as bronchoconstriction and dyspnoea, as well as an increased susceptibility to respiratory infections. Carbon monoxide can impair the function of important organs, such as the brain and the heart, by binding to hemoglobin and affecting its capability to transfer oxygen (Kampa & Castanas, 2008).

In addition to harming human health, air pollution can have a detrimental effect on the environment. Sulfur and nitrogen oxides can contribute to the formation of acid rain, which acidifies water and soil, damaging plants and marine organisms. Ozone reduces carbon dioxide transfer in plants, impairing photosynthesis. Like humans, wildlife can experience health problems caused by pollutants, such as reproductive failure (Manisalidis et al., 2020).

PM2.5 is fine particulate matter with particles that are 2.5 microns or less in diameter. Exposure to PM2.5 has been found to be associated with various harmful health effects, such as lung inflammation and blood coagulation (Kampa & Castanas, 2008), as well as premature mortality, acute and chronic bronchitis, and asthma attacks (California Air Resources Board, n.d.-b). Long-term PM2.5 exposure has also been found to be associated with pneumonia and lung and kidney cancer (Mainka & Żak, 2022). Children exposed to PM2.5 are particularly susceptible to health issues and have been found to have slower lung growth. PM2.5 is produced by wildfires, as well as industrial processes, motor vehicle usage, and agriculture. It can also be formed from gasses, such as sulfur dioxide, nitrogen oxides, and certain organic compounds, reacting in the atmosphere (California Air Resources Board, n.d.-b).

Carbon monoxide (CO) is a gas that is colorless and odorless. It can bind to hemoglobin and reduce the ability of blood to transfer oxygen, which can impair the function of important organs (Kampa & Castanas, 2008). Exposure to CO can cause fatigue, headaches, confusion, and dizziness due to blood being unable to properly carry oxygen to the brain, and inadequate amounts of oxygen delivered to the heart can cause chest pain. CO can also indirectly contribute to global warming, as it contributes to chemical reactions that cause increases in ozone, a gas that causes climate change. CO is often produced by the incomplete combustion of carbon-containing compounds, which occurs in wildfires, as well as power plants, motor vehicles, and incinerators (California Air Resources Board, n.d.-a).

Nitrogen dioxide (NO2) is a highly reactive gas found in air pollution. Although the impacts of NO2 on human health is not well understood, NO2 exposure has been found to be linked to pneumonia-related hospitalizations (Mainka & Żak, 2022), as well as the development of asthma and the aggravation of respiratory diseases (EPA, 2023a). In addition to harming human health, NO2 can have detrimental effects on the environment. It can react with other chemicals to form acid rain, which can be harmful to ecosystems. NO2 is primarily formed in the burning of fuel in sources like motor vehicle emissions and power plants (EPA, 2023a), and it is also found in wildfire smoke (Durán, 2014).

Sulfur dioxide (SO2) is a gaseous air pollutant. It has been found to be linked to various health problems related to the human respiratory, cardiovascular, and nervous systems, as well as type 2 diabetes, particularly when combined with other air pollutants (Khalaf et al., 2022). Short-term exposures can cause breathing difficulties, especially in people with asthma and children. Sulfur oxides can also cause environmental harm by damaging foliage and hindering growth of trees and plants. Like NO2, SO2 can contribute to the formation of acid rain, which can be harmful to plants and wildlife

(EPA, 2023b). SO2 is often emitted from fossil fuel combustion in industrial processes (EPA, 2023b), and it is also produced by wildfires (Durán, 2014).

Wildfires are a significant source of air pollutants that can travel over long distances and cause health problems in areas far from the fires themselves (Requia et al., 2021). In the United States, an average of 7.0 million acres per year have been burned since 2000—double the annual average of 3.3 million acres in the 1990s (Congressional Research Service, 2023). The burning of wildfires creates smoke, which contains various pollutants including nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and sulfur dioxide (SO2) (Durán, 2014).

Since air pollutants are associated with serious environmental and health issues, it is important to understand the amount of pollution that different sources produce. While the components of wildfire smoke have been studied before, there is a lack of research on whether those components actually have a significant impact on the overall level of specific air pollutants. This paper shows the impact of wildfire smoke on air pollution compared to other sources of emissions, evaluating whether wildfires are a notable source of each pollutant. By understanding how strongly wildfires impact the concentrations of individual pollutants in the air compared to other sources of pollution, we can more effectively reduce the damage done by air pollutants to human health and the environment.

METHODS

The wildfire data, "1.88 Million US Wildfires", is from an SQLite database used by the United States' Fire Program Analysis system (Short, 2017). It consists of information about 1.88 million wildfires in the United States between 1992 and 2015. The approximate number of acres burning each day was added to the dataset by summing the final sizes of every fire burning on each day. A fire was considered burning on a date when the date fell between the fire's discovery and containment dates.

The air pollution data, "Historical Air Quality", is a regularly updated database on Kaggle provided by the US Environmental Protection Agency Air Quality System Data Mart (United States Environmental Protection Agency, n.d.). It contains every value collected via the ambient air monitoring program of the EPA. PM2.5 was measured in micrograms per cubic meter, SO2 and NO2 was measured in parts per billion, and CO was measured in parts per million. The PM2.5 data in the dataset was collected using the Federal Reference Method (FRM). The daily mean value of each pollutant was added to the data by averaging every daily mean value measured on the same day.

The air quality and wildfire data was limited to information from California and filtered by year; the dates were converted into a consistent date-time format. The necessary data for graphing was then compiled into a single dataset using the date variable from both datasets. The data from the two categories (the fire size in acres and the mean measurement of the pollutant) was plotted in a double line graph, with the daily fire size and the mean measured value of the pollutant in the y-axes and the date in the x-axis. This process was repeated for each pollutant studied. A sample of the combined dataset is shown in Table 1 below.

	FIRE_SIZE	mean_pm25
date		
2007-01-01	8.7	32.166667
2007-01-02	6.0	36.033333
2007-01-03	8.2	20.633962
2007-01-04	2.8	15.006667
2007-01-05	718.9	4.986667

Table 1. Sample from the combined dataset for PM2.5 in 2007.

RESULTS

PM2.5

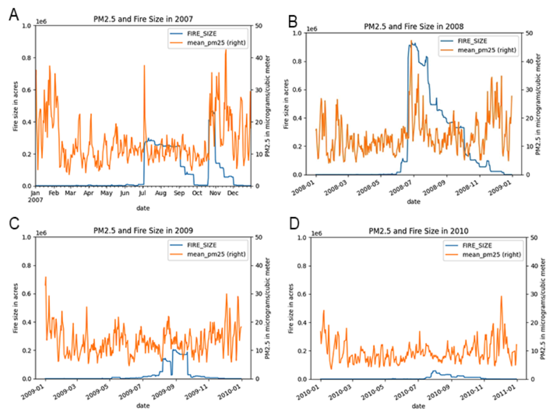

Figure 1. California fire sizes in acres (blue) and PM2.5 levels in micrograms per cubic meter (orange) over time in 2007, 2008, 2009, and 2010.

In Figure 1A, the beginning of the first major increase in wildfire size in July 2007 is closely followed by a strong spike in PM2.5. However, the PM2.5 measurements quickly return to their previous level, while there is only a slight decrease in wildfire size. The sharp decrease in PM2.5 is not reflected in the fire size. The steep increase in fire size in November is also very closely followed by a large increase in PM2.5.

More noticeably, the drastic increase in wildfire size in Figure 1B is immediately followed by a notable spike in the mean value of PM2.5, showing a strong link between the fires and the concentration of PM2.5 in 2008. The decrease in fire size is also mirrored by the change in PM2.5.

Figure 1C shows that there are some relatively small wildfires in 2009, mostly between August and October. The PM2.5 concentration experiences a slight increase during that period. It is higher than the concentration during the same time period in 2010, which was accompanied by a smaller fire size; this shows that the increase in PM2.5 is likely related to the increase in wildfires.

As depicted in Figure 1D, there is very little fire in 2010; most changes in PM2.5 are likely not associated with wildfires. The higher values of both fire sizes and PM2.5 in 2009 compared to 2010 suggest that the increases in the two values are linked.

Due to the increases in fire sizes in all four years graphed being linked to notable increases in PM2.5 levels, PM2.5 was closely connected with fire size between 2007 and 2010. Burning from wildfires is therefore likely a significant contributor to overall PM2.5 concentrations. PM2.5 levels are also consistently higher during winter months.

Carbon Monoxide

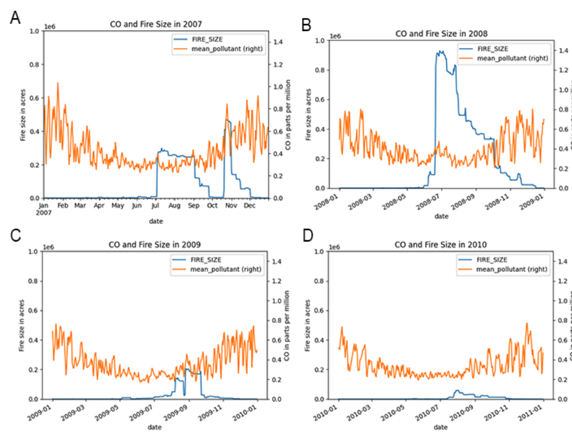

Figure 2. California fire sizes in acres (blue) and CO levels in parts per million (orange) over time in 2007, 2008, 2009, and 2010.

In Figure 2A, the increase in burning in July is followed by a minor increase in CO. The larger increase in burning in November is immediately followed by a larger increase in CO, but the high levels of CO continue even as the wildfires are contained. Although the CO increase in November appears to be correlated with the increase in fires, the other panels show that CO consistently increases during autumn and winter months, suggesting that wildfires are not the only factor that caused the CO levels to increase in November.

In Figure 2B, the large spike in fire size is followed by an increase in CO concentration, and the CO level decreases as the wildfire size decreases. However, the change in CO level is relatively small, suggesting that even the amount of CO produced by large wildfires is not a very significant part of the overall CO levels.

The fires in Figure 2C appear to have some correlation with any change in CO level: although the changes are very small, there is an increase in CO when fire sizes increase.

In Figure 2D, the very small wildfires between July and November 2010 do not have any visible correlation with the level of CO.

Nitrogen Dioxide

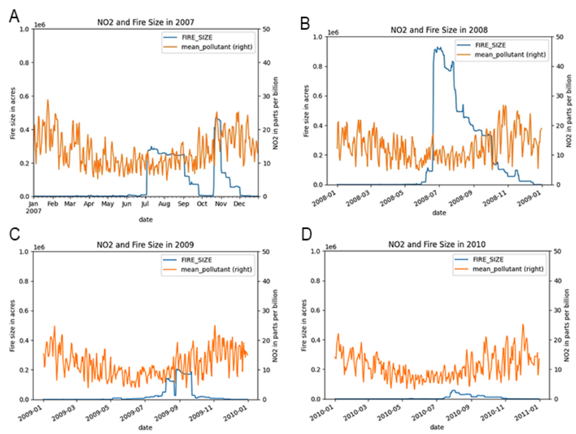

Figure 3. California fire sizes in acres (blue) and NO2 levels in parts per billion (orange) over time in 2007, 2008, 2009, and 2010.

The fires between July and October 2007 in Figure 3A do not appear to be correlated with any changes in NO2. The large increase in fires in October and November seem to be associated with an increase in NO2.

The large increase in fires in Figure 3B is associated with some small increases in NO2. However, the level of NO2 actually declines while the fire sizes are high, suggesting that the fires were not a notable contributor to the NO2 level in 2008.

In Figure 3C, the values of NO2 appear to increase during the second spike in wildfire burning. However, the level of NO2 is not significantly different from the levels during the smaller fires in Figure 3D, indicating that the wildfires in 2009 were not a major contributor to the level of NO2.

In Figure 3D, the shapes of the fire size and mean pollutant lines appear to be unrelated, showing that correlation between the small fire size and the mean value of NO2 is unlikely.

Sulfur Dioxide

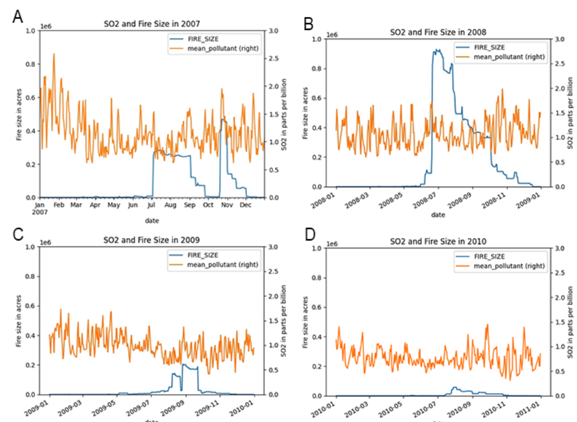

Figure 4. California fire sizes in acres (blue) and SO2 levels in parts per billion (orange) over time in 2007, 2008, 2009, and 2010.

In Figure 4A, fire sizes do not seem to be closely linked with the level of SO2. Although the spike in fires in November appears to be associated with an increase in SO2, the level of pollution during the rest of the fires is mostly unrelated to the fire size. The level of SO2 is unusually high at the beginning of the year, but it is not associated with any wildfires, so there was likely an increase in a different source of SO2 at the beginning of the year.

In Figure 4B, the shape of the SO2 graph is similar to the fire size graph between June and October 2008. As the fire size suddenly increases in July, the pollutant level increases accordingly and decreases as the fire size decreases. However, at the end of the year, the mean SO2 level increases despite the fire size decreasing, suggesting that there were different factors that also significantly affected SO2 levels. The graph shows a correlation between the two variables, but it does not seem to be very strong as the very drastic increase in fire size only leads to a minor increase in SO2.

In Figure 4C, the first noticeable increase in fire size is not associated with any notable increase in SO2. However, the second period of slightly larger fires is immediately followed by a small increase in pollution, and the pollution level decreases as the fires become smaller. There may have been fewer non-wildfire factors contributing to SO2 levels in 2009 than 2007, as a relatively small increase in fires in September 2009 (Figure 4C) is more closely correlated with an increase in SO2 pollution than the larger increase in July 2007 (Figure 4A).

In Figure 4D, the series of very small fires between July and November 2010 do not appear to be associated with any noticeable change in SO2 levels.

Comparison

PM2.5 concentrations are shown to be significantly influenced by the amount of wildfire burning. Increases in wildfire sizes are consistently followed by large spikes in PM2.5 levels, which is particularly noticeable in Figure 1A. In comparison, the graphs about CO data show that the connection between wildfires and CO concentration is weaker, as the changes in pollution are less extreme compared to PM2.5. However, there are still many similarities in the shapes of the plotted fire size and pollutant lines, suggesting that wildfires are still a notable factor in the level of CO in the air. Out of the four pollutants studied, NO2 levels appear to be the least related to fire size, as even the largest fires in 2008 (Figure 3B) are only linked to a small increase in NO2, and all four years show minimal relationships between the two factors. SO2, although more closely related than NO2, also has a relatively small connection with fire size. There are similarities between the shapes of the lines in the graphs, but most of the notable changes in sulfur dioxide are not associated with wildfire sizes.

Despite previous studies showing that both SO2 and NO2 are notable pollutants produced by wildfires (Durán, 2014), the data shown in this paper shows very small amounts of correlation between wildfires and the levels of SO2 and NO2. This could suggest that while wildfires produce these pollutants, there are other sources that produce much higher levels of these pollutants, making the pollution from wildfire smoke less significant compared to the overall pollution levels. In contrast, there is a much more noticeable link between wildfires and PM2.5 levels, suggesting that wildfires may be one of the main sources of PM2.5.

CO and NO2 levels are shown by the line graphs to be consistently much higher during the beginning and end of each year, during the winter. This could potentially be a result of the fact that low levels of NO2 and CO in summer months have been attributed to the role the compounds play in the photochemical reactions involving solar radiation that form ozone (Cichowicz et al., 2017). When the amount of sunlight is reduced during wintertime, the rate of photochemical reactions is reduced, increasing the time the pollutants spend in the atmosphere before reacting (Voiculescu et al., 2020). These seasonal patterns may also be attributed to changes in anthropogenic emissions, such as an increase in fuel burning for heating and vehicle usage during the winter due to the cold weather. The PM2.5 graphs show a similar although less noticeable pattern, where the PM2.5 levels are generally higher at the beginning and the end of the year. However, the data used in this paper show minimal seasonal effects on SO2 pollution, as the SO2 graphs do not show the same downwards curve as the other graphs, where the pollutant levels are lower during the middle of the year.

CONCLUSION

Air pollutants can have harmful effects on health and the environment, so it is necessary to understand the contributions of different factors towards the concentration of different pollutants. This paper aims to investigate the effects of wildfires on the overall levels of four common air pollutants: PM2.5, carbon monoxide (CO), nitrogen dioxide (NO2), and sulfur dioxide (SO2). The analysis of wildfire and air pollution data suggests that in California during the time period studied, the number of acres of wildfires burning at a specific time is most strongly correlated to the level of PM2.5, and only slightly correlated with the level of CO, NO2, and SO2. The findings suggest that to significantly reduce the health and environmental impacts of PM2.5, it may be beneficial to take actions towards reducing the quantity and size of wildfires. However, the reduction of wildfires may be a less effective way of minimizing the harmful effects of the other three pollutants studied, as the relatively small correlation of CO, NO2, and SO2 with fire size indicates that there are other factors that more strongly influence the amounts of these pollutants. Although wildfires may affect these pollutants to some degree, it may be more effective to investigate and reduce other sources of these three pollutants, such as the burning of fossil fuels in industrial facilities and motor vehicles (California Air Resources Board, n.d.-a; EPA, 2023a, 2023b).

Further research could also be done on the causes of PM2.5, CO, and NO2 levels being higher during the winter, despite SO2 not having any notable seasonal patterns. While the CO and NO2 patterns can be attributed to the increased amount of sunlight and therefore ozone formation during the summer (Cichowicz et al., 2017), there is minimal information on the seasonal behavior of PM2.5 and the contrasting non-seasonal behavior of SO2.

The types of pollutants released by wildfires can vary depending on the environment, vegetation type, and climate. For example, fires in savannahs tend to produce more carbon dioxide, while fires in boreal forests produce more CO, methane, and PM2.5 (Durán, 2014). Further research could be done by investigating fires and pollutant levels with different regions or pollutant types to see how the patterns found in this paper will vary in other situations.

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