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Effect of environmental pollutants PM-2.5, carbon monoxide, and ozone on the incidence and mortality of SARS-CoV-2 infection in ten wildfire affected counties in California

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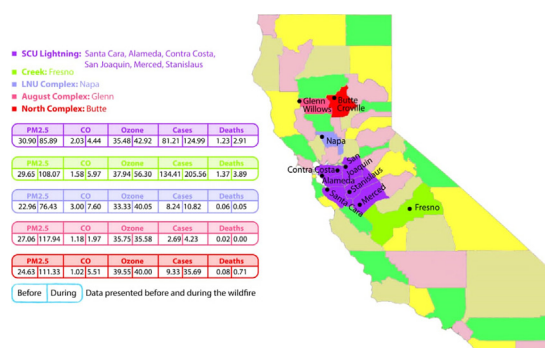
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HIGHLIGHTS

- Impact of wildfire pollutants on COVID-19 cases and deaths was examined in 10 counties in California.
- PM 2.5 concentration increased by 220.71%; CO by 151.05%, and O₃ by 19.56%.
- COVID-19 cases and deaths increased by 56.9%, and 148.21% respectively.
- PM-2.5, CO, and O₃ concentrations were temporally associated with increases in the incidence and mortality of COVID-19.

GRAPHICAL ABSTRACT



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ABSTRACT

Various regions of California have experienced a large number of wildfires this year, at the same time the state has been experiencing a large number of cases and deaths from Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). The present study aimed to investigate the relationship of wildfire allied pollutants, including particulate matter (PM-2.5 μm), carbon monoxide (CO), and Ozone (O₃) with the dynamics of new daily cases and deaths due to SARS-CoV 2 infection in 10 counties, which were affected by wildfire in California. The data on COVID-19 pertaining to daily new cases and deaths was recorded from Worldometer Web. The daily PM-2.5 μm , CO, and O₃ concentrations were recorded from three metrological websites: BAAQMD- Air Quality Data; California Air Quality Index-AQI; and Environmental Protection Agency- EPA. The data recorded from the date of the appearance of first case of (SARS-CoV-2) in California region to the onset of wildfire, and from the onset of wildfire to September 22, 2020. After the wildfire, the PM2.5 concentration increased by 220.71%; O₃ by 19.56%; and the CO concentration increased by 151.05%. After the wildfire, the numbers of cases and deaths due to COVID-19 both increased respectively by 56.9% and 148.2%. The California wildfire caused an increase in ambient concentrations of toxic pollutants which were temporally associated with an increase in the incidence and mortality of COVID-19.

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1. Introduction

Over the past three decades, the incidences of wildfires have markedly increased in the United States of America, mainly in California. Wildfire air contains smoke, gases, dust, fine particles and particulate matter (Bashir et al., 2020). Wildfire smoke contains a mixture of carbon dioxide, carbon monoxide, nitrogen oxides, particulate matter, hydrocarbons, and other organic compounds (Balme, 2018). Wildfire smoke and pollutants can travel far from the actual site of the wildfire, and pose various human health hazards and economical challenges. Smoke and particulate matter (PM_{2.5}) exposures are associated with various respiratory and cardiovascular illnesses as well as mortality. The most susceptible populations from exposure of wildfire smoke include middle-aged and older adults with acute or chronic respiratory and cardiovascular diseases, and pregnant women (Cascio, 2018). The same groups of people are also susceptible to SARS-COV-2 infections (Madjid et al., 2020; Meo et al., 2020e).

Presently, the United States of America is facing two major health care challenges: environmental pollution due to the wildfires, and an increasing number of SARS-COV-2 cases and deaths. Wildfires have burned nearly 7.7 million acres this year in the various states of USA, which has affected human lives and damaged economies (Hoover and Hanson, 2020). As of October 30, 2020, the total number of documented SARS-COV-2 cases in USA was 9,217,960 out of a worldwide total number of cases of SARS-COV-2 of 45,496,299. The total number of SARS-COV-2 cases in California at this time was 925,055, which is 10.03% of the total number of cases in the USA (Worldometer, 2020).

Weather conditions and environmental pollution can have an impact on the pattern of health and disease (Meo et al., 2020a). Environmental pollution can promote the transportation of microbes and SARS COV-2 infection (Bo Wang et al., 2020; Bilal et al., 2020). Environmental pollution, including wildfire allied pollutants enter into the lungs, blood circulation, deposit in various organs of the human body and cause severe illness and death. This study aimed to investigate the relationship of wildfire allied pollutants, including particulate matter (PM-2.5 μm), CO, and O₃ with the dynamics of new daily cases and deaths due to SARS-COV 2 infection in 10 counties, which were affected by wildfire in California, USA.

2. Research methodology

In this study, we selected 10 different counties from the state of California (USA), which were affected by wildfire. The wildfires and the affected counties included (1) SCU Lightning Complex: Santa Clara, Alameda, Contra Costa, San Joaquin, Merced, and Stanislaus Counties; (2) Creek Complex: Fresno County; (3) LNU Complex: Napa County; (4) August Complex: Glenn County; and (5) North Complex: Butte County (see the Figure Graphical Abstract).

In recent months, these ten counties in California were affected by wildfire and its associated pollution, smoke, dust, and particulate matters (both fine and ultrafine). Daily information on meteorological conditions, wildfire pollutants, particulate matter (PM-2.5), CO levels, and O₃ levels was obtained from three metrological Websites: (BAAQMD-Air Quality Data, 2020); (California Air Pollution: Air Quality Index-AQI, 2020); and (Environmental Protection Agency -EPA, USA, 2020).

The data were divided into two groups, before (Group A) and during the wildfire (Group B) in the ten counties in California. The daily levels of particulate matter (PM-2.5 μm), CO, and O₃ and the daily new cases and daily deaths were recorded from the date of the appearance of first case of SARS-CoV-2 in 10 different counties in California region from March 19, 2020 to August 15, 2020 (Group A); and from the occurrence of wildfire from August 15, 2020 to Sept 22, 2020 (Group B). The data on daily cases and daily deaths due to the COVID-19 pandemic, were collected from the Web (Worldometer, 2020).

The data was analyzed using R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical

Computing, Vienna, Austria. High-low-close charts were prepared to depict the collated information of four characteristics (cases, deaths, pollutant parameters and groups). Mean \pm SEM has been reported for quantitative variables. Normality of data for Normal and Poisson distributions was checked through one-sample Kolmogorov-Smirnov test. Welch *t*-test was applied to compare the mean differences between two groups with the number of cases, deaths and pollutant parameters. Binary Logistic Regression analysis was also performed to observe the log-odds in groups when compared with the number of cases, deaths and pollutant parameters. Spearman Rho correlation was applied to assess the relationship between various meteorological factors at 1% level of significance, whereas, Poisson Regression analysis was performed to predict the number of cases and deaths from PM_{2.5}, O₃ and CO after fulfilling the assumptions. Goodness of Fit tests and Model tests for all regression analysis were significant. An $\alpha = 0.05$ and 0.01 were considered as statistically significant.

3. Results

The environmental pollutants' mean values for PM_{2.5}, CO and O₃ each significantly increased during the wildfire compared to before the wildfire. The increase for the PM_{2.5} level was 220.71%, for the O₃ level was 19.56%, and for the CO level was 151.05% ($p < 0.001$ for each). The average number of SARS-COV-2 cases and deaths significantly increased during the wildfire as compared to before the onset of wildfire. The percentage increase in the number of cases was 56.9%, and for deaths was 148.21% ($p < 0.001$ for each) (see Table 1). The PM-2.5 μm , CO, and O₃ levels and daily new cases and daily deaths were further analyzed based by combining county data into total pollution levels and cases/deaths for all counties affected in each of five different fire zones (Figure Graphical Abstract). However, there was no change in the number of deaths while comparing these complexes before the wildfire and up to one month after the wildfire (Figs. 1, 2 and 3).

The binary logistic regression analysis results are presented in Table 2. The categorical dependent variable depends on the same division of Groups A and B. It was used to predict the number of cases, deaths, and pollutant parameters. The values of model chi-square and Hosmer-Lemeshow were 1035.43 and 25.93, respectively. Both chi-square values were significant at 1% level of significance, confirming that the fitted model was appropriate. The classification table obtained from the logistic model showed an overall accuracy of 91.5%. The Nagelkerke R² value was 66.2%. After the start of wildfire (Group A), compared to before the wildfire (Group B), the number of cases (adjusted odds ratio, AOR = 1.886; 95% CI = 1.427–1.997), deaths (AOR = 1.140; 95% CI = 1.076–1.209), PM_{2.5} (AOR = 1.068; 95% CI = 1.059–1.077), O₃ (AOR = 1.025; 95% CI = 1.015–1.036) and CO (AOR = 1.476; 95% CI = 1.336–1.632) all significantly increased.

The mean number of new cases of COVID-19 in each of the five fire zones was compared for the periods of before (Group A) and after (Group B) the onset of wildfire. The number of new cases of COVID-19 was significantly higher in Group B compared to Group A for all five

Table 1

Comparison between particulate matter PM_{2.5}, Carbon monoxide, ozone and mean number of new SARS-COV-2 cases and deaths in ten different counties in California.

Parameters	Group A (n = 1488) Mean \pm SEM	Group B (n = 390) Mean \pm SEM	% Increase	p-Value
PM _{2.5} (ppm)	28.97 \pm 0.411	92.91 \pm 2.54	220.71%	<0.001*
CO (ppm)	1.90 \pm 0.04	4.77 \pm 0.22	151.05%	<0.001*
O ₃ (DU)	35.94 \pm 0.373	42.97 \pm 0.95	19.56%	<0.001*
Cases (n)	64.13 \pm 2.65	100.62 \pm 5.03	56.9%	<0.001*
Deaths (n)	0.89 \pm 0.05	2.21 \pm 0.211	148.21%	<0.001*

Group A: Data presented from appearance of first case of SARS-COV 2 in these counties March 19, 2020 to the beginning of wildfire August 15, 2020. Group B: Data presented from the beginning of wildfire August 15, 2020 to Sept 22, 2020.

* Statistically significant at 5% level of significance.

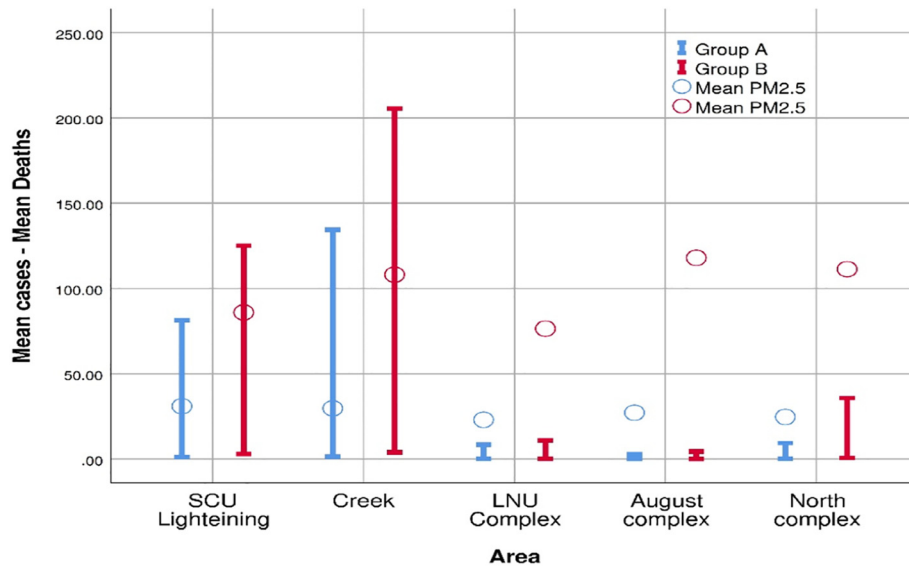


Fig. 1. Comparison of SARS-COV-2 cases and deaths with PM-2.5 before and after the wildfire.

fire zones. However, in Group B, the number of deaths significantly higher in the SCU Lightning and Creek zones as compared to Group A (Tables 3, 4).

The rho-coefficient relation showed a significantly increased number of new cases and deaths with increasing levels of PM2.5 and CO, however, for increasing levels of O₃ there was a significant relationship with new cases but an insignificant relationship with deaths (see Table 5). When area-wise correlations were studied before and after the onset of wildfire, in SCU Lightning, with increasing levels of PM2.5, CO, and O₃ the number of new cases significantly increased, whereas deaths were positively correlated with increasing levels of PM2.5 and CO but not O₃. An increasing trend was observed in the Creek area where the number of cases and deaths had a positive relationship with PM2.5, O₃ and CO. In LNU Complex a significant rise was observed in the number of cases with the increase in PM2.5 and CO, whereas deaths had no relationship with the pollutant parameters. The number of cases in the August Complex had a significant positive

correlation with PM2.5 and CO, however, the relation of pollutant parameters with deaths was not significant. In the North Complex, the number of cases and deaths significantly increased with the increase in PM2.5 and CO levels, whereas O₃ level had no relationship with the cases and deaths. These results are presented in Figs. 4–6. While applying Poisson regression analysis it was found that, after the commencement of wildfire, with an increase of 1 μm in PM_{2.5} level, the number of deaths significantly increased by 0.4%. With the increase of 1 unit in O₃ level, a similar trend was observed in the number of cases and deaths (Table 6).

4. Discussion

Presently, the United States of America is facing two major challenges of intermittent pollution associated with wildfire and an ongoing COVID-19 pandemic. California, which is one of the largest states in the USA, has many counties that have been affected by wildfire. The major

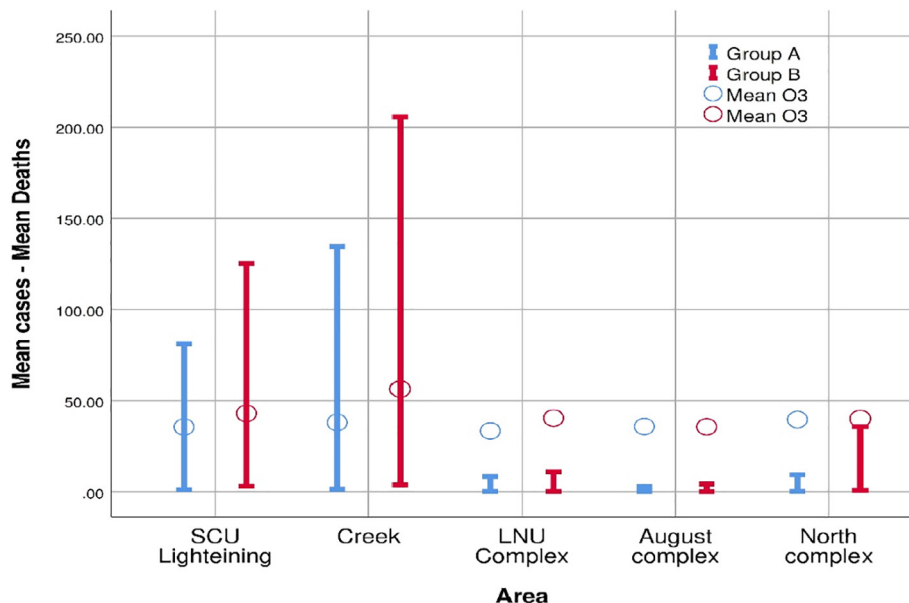


Fig. 2. Comparison of SARS-COV-2 cases and deaths with O₃ before and after the wildfire.

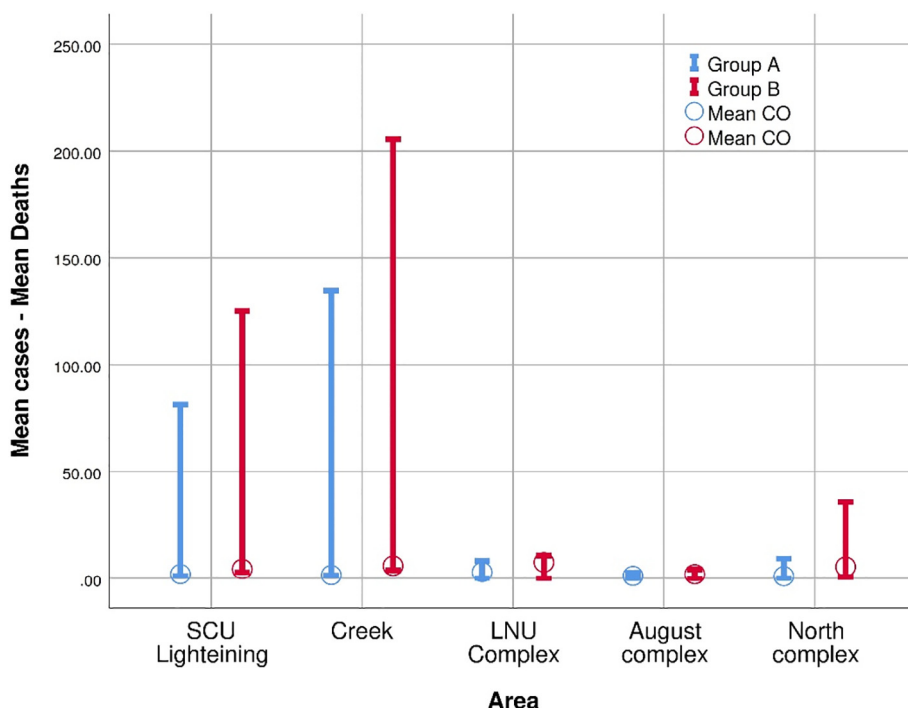


Fig. 3. Comparison of SARS-COV-2 cases and deaths with CO before and after the wildfire.

pollutant components of wildfire are smoke, particulate matter (PM-2.5), CO, O₃ and other substances. The present study has demonstrated that the particulate matter PM-2.5, CO, and O₃ are all significantly increased in 10 different counties in California that have been affected by wildfire. These pollutants have a positive association with an increased number of SARS-COV-2 daily cases and daily deaths in the wildfire allied counties in California, USA, that we studied.

The epidemiological and environmental toxicological literature demonstrates a relationship between air pollution and an increased

Table 2

Binary Logistic Regression showing the relation between cases, controls, and pollutant factors with groups.

Parameters	B	S.E.	Wald	p-Value	Adjusted odds ratio	95% C.I.
Cases (n)	0.776	0.032	63.22	<0.001*	1.886	1.427 1.997
Deaths (n)	0.131	0.030	19.50	<0.001*	1.140	1.076 1.209
PM2.5 (ppm)	0.066	0.004	251.28	<0.001*	1.068	1.059 1.077
O ₃ (DU)	0.025	0.005	21.73	<0.001*	1.025	1.015 1.036
CO (ppm)	0.390	0.051	58.33	<0.001*	1.476	1.336 1.632

S.E = Standard Error. β = Coefficient Estimates; Exp (β) = Exponentiated values; Wald = explanatory variables.

* Statistically significant at 5% level of significance.

Table 3

Comparison of SARS-COV-2 cases in five different fire zone complexes in California before and after the onset of wildfire.

Counties	Group A Mean ± SEM	Group B Mean ± SEM	% Increase	p-Value
SCU Lightning	81.21 ± 3.49	124.99 ± 5.52	53.91%	<0.001*
Creek Complex	134.41 ± 12.43	205.61 ± 22.45	53.0%	0.009*
LNU Complex	8.24 ± 0.95	10.82 ± 0.68	31.31%	0.030*
August Complex	2.69 ± 0.33	4.23 ± 0.67	57.25%	0.041*
North Complex	9.33 ± 1.35	35.69 ± 4.44	282.53%	<0.001*

Group A: Data presented from the appearance of first case of SARS-COV 2 in these counties March 19, 2020 to the beginning of wildfire August 15, 2020. Group B: Data presented from the beginning of wildfire August 15, 2020 to Sept 22, 2020.

* Statistically significant at 5% level of significance.

incidence of cardiopulmonary diseases (Seposo et al., 2020). The literature has established a relationship between exposure to ecotoxicity, genotoxicity, and oxidative potential of particle matter, and an increased susceptibility to and morbidity from respiratory infections (Romano et al., 2020). Kan et al. (2005) demonstrated that each 10 micrograms per cubic meter increase in respirable particulate matter PM-2.5 and MP-10, is associated with a 6% increased relative risk of mortality during a coronavirus outbreak. Similarly, Paital and Agrawal (2020) identified a relationship between PM2.5 levels, ambient NO₂ concentrations, and ACE-2 expression all with severity of COVID-19 infections.

A few previous studies have also established an association between high concentration of ambient fine particles, particulate matter PM-2.5, and respiratory infections (Cannon et al., 2018; Gandini et al., 2018; Croft et al., 2020). The literature shows that environmental and climate

Table 4

Comparison of SARS-COV-2 deaths in five different fire zone complexes in California before and after the onset of wildfire.

Counties	Group A Mean ± SEM	Group B Mean ± SEM	% Increase	p-Value
SCU Lightning	1.23 ± 0.07	2.91 ± 0.26	136.59%	<0.001*
Creek	1.37 ± 0.27	3.89 ± 1.24	183.94%	0.003*
LNU Complex	0.05 ± 0.02	0.06 ± 0.05	20.0%	0.779
August Complex	0.00 ± 0.00	0.02 ± 0.01	-	0.374
North Complex	0.08 ± 0.03	0.71 ± 0.22	-	0.007*

Group A: Data presented from the appearance of first case of SARS-COV 2 in these counties March 19, 2020 to the beginning of wildfire August 15, 2020. Group B: Data presented from the beginning of wildfire August 15, 2020 to Sept 22, 2020.

* Statistically significant at 5% level of significance.

Table 5

Correlation between PM2.5, O₃ and CO with number of cases and deaths.

Parameters	Cases: rho-coefficient (p-value)	Deaths: rho coefficient (p-value)
PM2.5	0.403 (<0.001) *	0.171 (<0.001) *
O ₃	0.158 (<0.001) *	0.034 (0.144)
CO	0.362 (<0.001) *	0.173 (<0.001) *

p-Value significant at 1% level of significance.

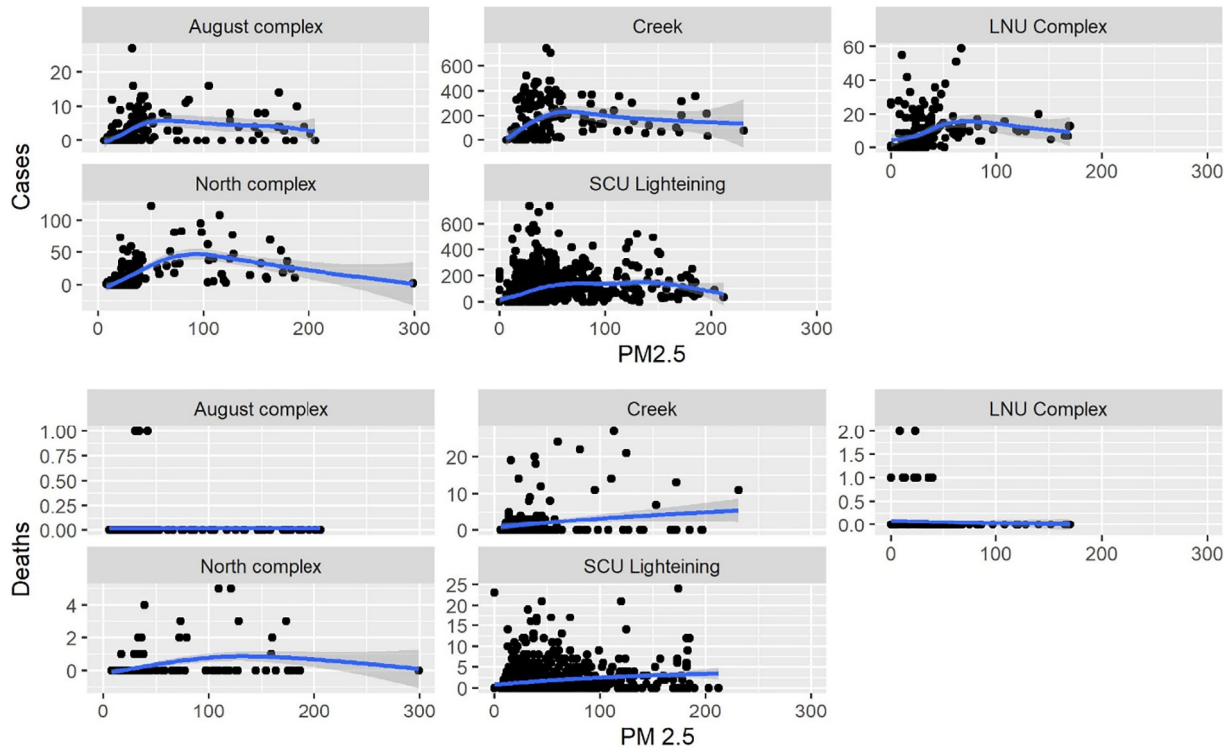


Fig. 4. Relationship of PM 2.5 with SARS-COV-2 cases and deaths.

conditions possibly affect the transmissibility and incidence of SARS-COV-2 infection (Meo et al., 2020b; Meo et al., 2020c).

Bianconi et al. (2020) demonstrated that exposure to PM_{2.5} and PM₁₀ was linked to COVID-19 cases and deaths. The authors concluded that air pollution played a role in the outbreak of COVID-19 cases in Italy. Similarly, Zhu et al. (2020) found a positive relationship between

air pollutants, PM_{2.5}, PM₁₀, CO, O₃ with COVID-19 infections in China. In another study, Frontera et al. (2020) reported that increased air pollutants PM_{2.5} and NO₂ work independently and synergistically to induce a high incidence of mortality because of SARS-CoV-2 infections.

Furthermore, Bilal et al. (2020) performed a study on the environmental pollutants, climate indicators and the COVID-19 cases,

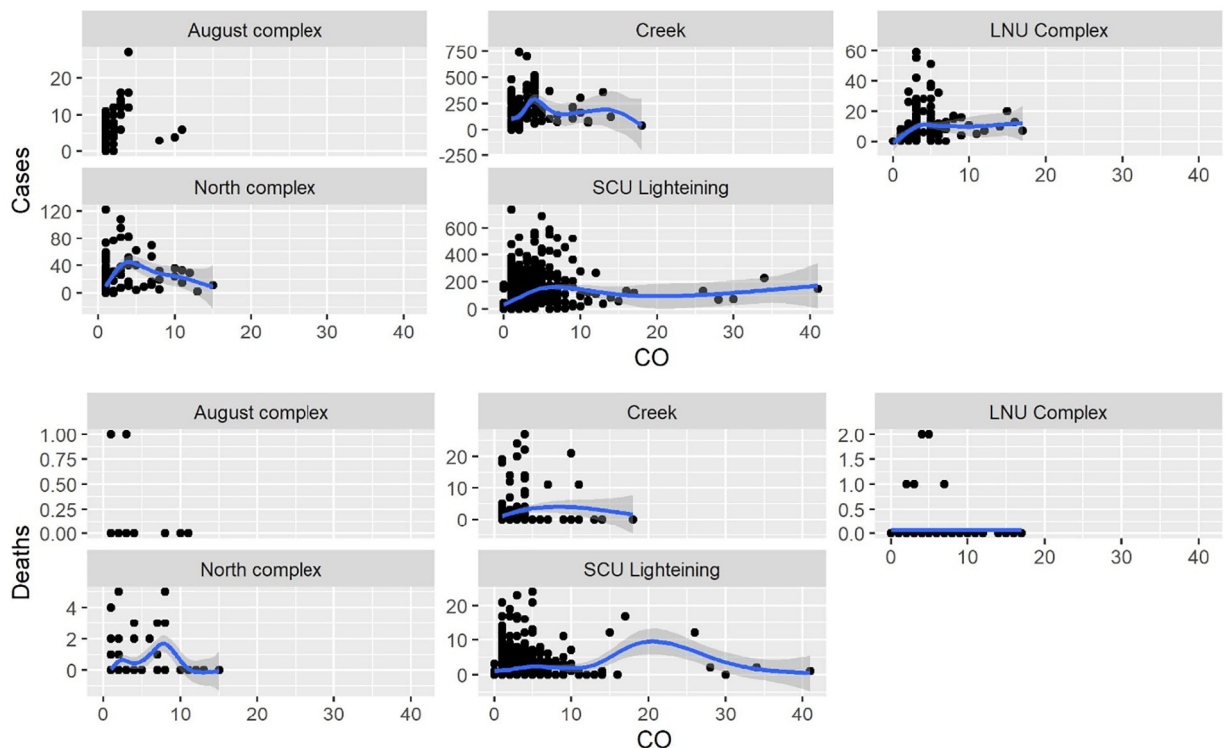


Fig. 5. Relationship of CO with SARS-COV-2 cases and deaths.

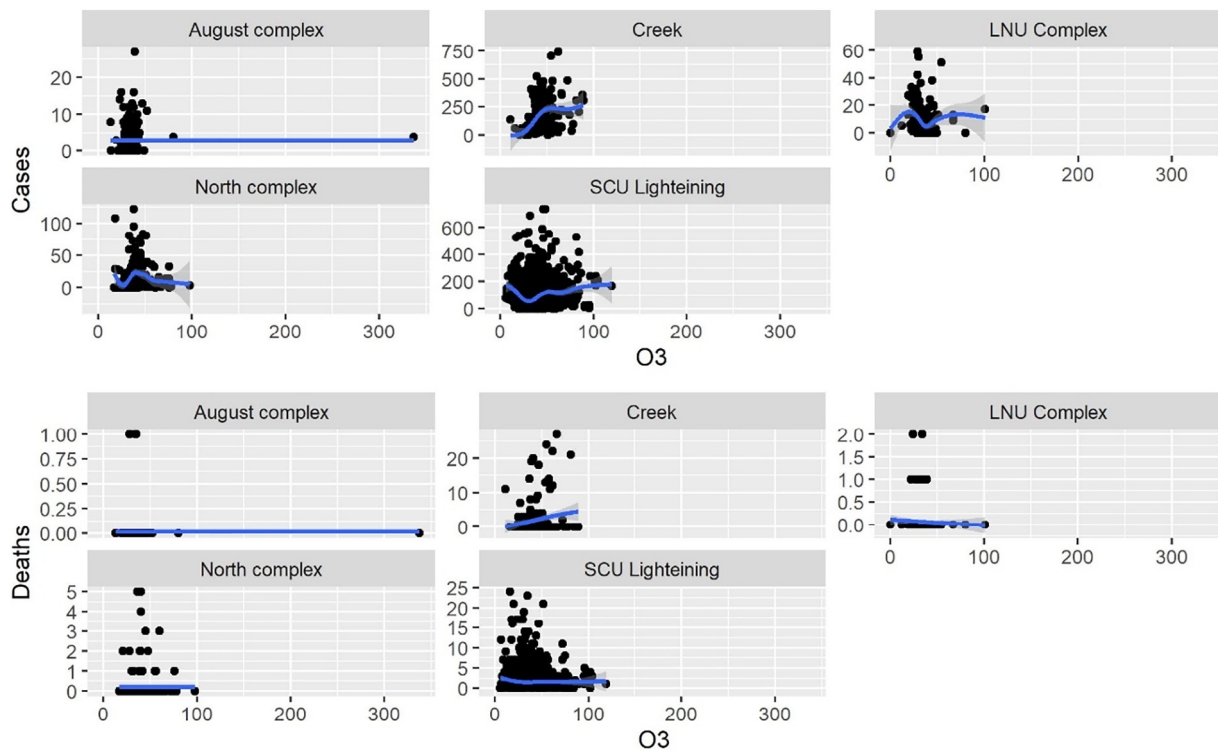


Fig. 6. Relationship of O₃ with SARS-COV-2 cases and deaths.

recoveries, and deaths in Germany. The authors reported that PM_{2.5}, O₃, and NO₂ each have a significant relationship with the outbreak of COVID-19. Low temperature and low humidity are significant climate indicators which have correlated with the spread of COVID-19 (Ma et al., 2020). In another study Bashir et al. (2020) appraised the correlation between environmental pollutants and COVID-19 outbreak in California. Their study findings demonstrated that environmental pollutants including PM₁₀, PM_{2.5}, SO₂, NO₂, and CO have a significant correlation with the COVID-19 epidemic in California. Moreover, Chakrabarty et al. (2020) reported that long-term exposure to air pollution, PM_{2.5} renders a population more susceptible to COVID-19 in USA. Similarly, Paital (2020) demonstrated that air pollution increases the risk of COVID-19 infection. In a recently published study Meo et al., (2020d) found that PM-2.5 and CO were reported to have a positive association with an increased number of SARS-COV-2 daily cases, cumulative cases, and cumulative deaths in San Francisco. Similarly, the present

study findings show an COVID-19 cases and deaths were associated with wildfire allied environmental pollutants PM_{2.5}, CO and O₃ in 10 different counties in California, USA. One of the reasons for the rising incidence of SARS-COV-2 cases in California may be its low air quality and high environmental pollution, which could make California more susceptible to respiratory-mediated infectious diseases such as COVID-19 (Bashir et al., 2020).

There is a debate in the science community, whether there is a link between PM pollution and the COVID-19 pandemic (Conticini et al., 2020). This hypothesized linkage is supported by evidence that exposure to PM pollution has been found to be particularly high in wildfire regions where high numbers of COVID-19 cases and deaths have been reported. The literature has established some pathophysiological and epidemiological links between PM exposure and viral infections (Bo Wang et al., 2020). There is an association between airborne pollution and the incidence of COVID-19 (Bianconi et al., 2020). Environmental pollution, especially particulate matters, acts as a carrier of the virus, impairs immunity, and causes people to be more susceptible to pathogens (Zhou et al., 2020). Moreover, fine particulate matter PM-2.5, CO, and O₃ all can induce a series of adverse health effects including inflammation, oxidative damage, and DNA damage to the lungs, which can trigger pulmonary and cardiovascular diseases through cytotoxicity mechanisms. Thus, a variety of lines of evidence support the hypothesis that exposure to air pollutants could play a significant role in the spread of COVID-19 (Seposo et al., 2020; Zoran et al., 2020).

We have found evidence that strengthens the hypothesized casual linkage between particulate matter PM-2.5, CO and O₃ generated by wildfire and the epidemiological dynamics of COVID 19 cases with mortality. The present study's findings are consistent with evidence that particulate matter PM_{2.5} is an efficient carrier or transport vector for SARS-COV-2 virus, and also promotes entry by viruses into the respiratory tract and where they can cause infections (Setti et al., 2020). Moreover, PM_{2.5} and carbon monoxide are highly toxic, exposure to which can result in damage to the lungs. These mechanisms of lung injury due to wildfire-generated pollutants support the hypothesis that

Table 6
Poisson Regression PM_{2.5}, O₃, and CO relation with the number of cases and deaths.

Group		PM _{2.5}	B¥	S.E	Exp (β)	p-Value
Group A	PM _{2.5}	Cases	0.002	0.0005	1.002	p < 0.001*
		Deaths	-0.011	0.0022	0.989	p < 0.001*
	O ₃	Cases	0.0001	0.0004	1.000	p < 0.001*
		Deaths	-0.010	0.0022	0.990	p < 0.001*
CO	Cases	-0.002	0.0002	1.002	0.632	
	Deaths	0.002	0.0081	1.001	0.823	
Group B	PM _{2.5}	Cases	-0.001	0.0004	0.999	p < 0.001*
		Deaths	0.004	0.0013	1.004	0.002*
	O ₃	Cases	0.001	0.0007	1.001	p < 0.001*
		Deaths	-0.006	0.0019	0.994	0.001*
CO	Cases	0.000	0.0002	1.000	0.150	
	Deaths	-0.001	0.0058	0.999	0.838	

S.E = Standard Error; β = Coefficient Estimates; Exp (β) = Exponentiated Values. ¥Controlled for temporal trends [date, day of week and weekends].

* Statistically significant at 5% level of significance.

wildfire pollutants particulate matter (PM-2.5), carbon monoxide, and ozone resulted in a recent increase in new SARS-COV-2 cases and deaths in ten counties in California.

4.1. Study strengths and limitations

This is the first study in literature, to our knowledge, that has investigated the effect of wildfire-allied major pollutants, including PM-2.5, CO, and O₃ on the incidence and mortality trends of SARS-COV-2 infections in 10 different counties in California. We selected the main pollutants, PM-2.5, CO and Ozone, because these pollutants penetrate deeply into the lungs. Moreover, we selected 10 different counties which were affected by wildfire. The daily new cases, daily deaths, and concentrations of PM-2.5 μm, CO, and O₃ were recorded during two time periods. The first time period spanned the date of the appearance of first case of (SARS-CoV-2) in California (which was March 19, 2020) through a recent outbreak of wildfire (which was August 15, 2020). The second time period spanned the onset of wildfire (which was August 15, 2020) to Sept 22, 2020 (which was a period of almost 7 weeks, that was sufficient for the wildfire to affect the incidence of COVID-19). A limitation of this study is that we were unable to collect data for other pollutants, such as PM10 and carbon dioxide, both of which may also affect the dynamics of the COVID-19 epidemic. Another limitation is that new COVID-19 cases and deaths can fluctuate in frequency for other reasons besides pollution. These reasons could include temperature, humidity, changes in societal patterns of social distancing and mass gatherings or adherence to wearing masks.

5. Conclusions

This study demonstrated that daily mean particulate matter PM-2.5, CO, and O₃ concentrations significantly increased after wildfire in ten counties in California. These pollutants were temporally associated with daily cases and daily deaths due to SARS-COV-2. Further study can elucidate the relative contribution to this association of wildfire, as well as potential contributions of demographic, social, therapeutic, and other environmental factors.

CRedit authorship contribution statement

Sultan Ayoub Meo: Conceptualization, supervision, analysis, writing-reviewing and editing. Abdulelah Adnan Abukhalaf, Ali Abdullah Alomar, Omar Mohammed Alessa: data collection and data entry, WS: data analysis, DCK: review and editing.

Declaration of competing interest

Authors declare no conflicts of interest.

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