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Research article

Do wildfires exacerbate COVID-19 infections and deaths in vulnerable communities? Evidence from California

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ABSTRACT

Understanding whether and how wildfires exacerbate COVID-19 outcomes is important for assessing the efficacy and design of public sector responses in an age of more frequent and simultaneous natural disasters and extreme events. Drawing on environmental and emergency management literatures, we investigate how wildfire smoke ($PM_{2.5}$) impacted COVID-19 infections and deaths during California's 2020 wildfire season and how public housing resources and hospital capacity moderated wildfires' effects on COVID-19 outcomes. We also hypothesize and empirically assess the differential impact of wildfire smoke on COVID-19 infections and deaths in counties exhibiting high and low social vulnerability. To test our hypotheses concerning wildfire severity and its disproportionate impact on COVID-19 outcomes in socially vulnerable communities, we construct a county-by-day panel dataset for the period April 1 to November 30, 2020, in California, drawing on publicly available state and federal data sources. This study's empirical results, based on panel fixed effects models, show that wildfire smoke is significantly associated with increases in COVID-19 infections and deaths. Moreover, wildfires exacerbated COVID-19 outcomes by depleting the already scarce hospital and public housing resources in local communities. Conversely, when wildfire smoke doubled, a one percent increase in the availability of hospital and public housing resources was associated with a 2 to 7 percent decline in COVID-19 infections and deaths. For California communities exhibiting high social vulnerability, the occurrence of wildfires worsened COVID-19 outcomes. Sensitivity analyses based on an alternative sample size and different measures of social vulnerability validate this study's main findings. An implication of this study for policymakers is that communities exhibiting high social vulnerability will greatly benefit from local government policies that promote social equity in housing and healthcare before, during, and after disasters.

1. Introduction

The United States is facing an increasingly complex, challenging set of scenarios due to the confluence of the two most pressing global health threats — the rapid emergence of the COVID-19 pandemic and the continuously evolving climate crisis (Rodrigues et al., 2020; Salas et al., 2020; Shultz et al., 2020). Wildfires, storms, flooding, and droughts are among the most immediately apparent sources of displacement and disruption in the context of the pandemic (Phillips et al., 2020; Travaglio et al., 2021).

Many scholars have noted that climate hazards, which are increasing in frequency and intensity in the context of climate change, are likely to intersect with the COVID-19 outbreak and worsen its infections and deaths by impeding public health responses (Conticini et al., 2020; Deek, 2020; Delfino et al., 2009; Henderson, 2020). For example, wildfires occurring globally, such as in Washington state in the U.S., Australia, and England in 2020, have been demonstrated to directly affect the human respiratory system due to the toxicity of wildfire smoke and indirectly squeeze out medical and sheltering resources, thus increasing COVID-19 infections and deaths (Burke et al., 2021; Cortes-Ramirez et al., 2022; Henderson, 2020; Travaglio et al., 2021).

However, for local communities, the need to address wildfires may also impact their already tight emergency budgets, staffing, and health service resources, which could jeopardize COVID-19 infection control (Salas et al., 2020). In particular, these compound risks exacerbate the unfolding economic crisis and longstanding socioeconomic and racial

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disparities in ways that can increase the risk to specific populations and impede recovery (Phillips et al., 2020; Watkins and Gerrish, 2018; Wright and Merritt, 2020).

This paper is focused on the state of California because the wildfire season in 2020 was characterized by a record-setting year of burned acres, fire severity, and socioeconomic costs. Occurring at the same time, the COVID-19 pandemic in California was also severe, in part due to its population size and density as well as disparities in local response capacities (Keeley and Syphard, 2021). In this paper, we explore the direct and indirect effects of wildfires on COVID-19 infections and deaths and ask whether their compound effects are likely to disproportionately affect counties with different levels of social vulnerability. Specifically, we answer three questions: First, what are the direct effects of wildfire smoke (represented by $PM_{2.5}$) on COVID-19 infections and deaths? Second, to what extent have local government policies and responses in the form of hospital and public housing resources, respectively, helped to reduce the impacts of wildfire smoke on COVID-19 outcomes? Third, how have communities with different levels of socioeconomic vulnerabilities been impacted during the 2020 wildfire season?

2. Prior literature and hypotheses

Previous studies have demonstrated that COVID-19 is a disease affecting the respiratory system and that it is impacted by atmospheric factors such as atmospheric pollution and notably fine and coarse particulate matters such as $PM_{2.5}$ and PM_{10} (Contini and Costabile, 2020; Travaglio et al., 2021; Wu et al., 2020). Aguilera et al. (2021) report that the toxicity of $PM_{2.5}$ varies across different sources of emissions, and $PM_{2.5}$ from wildfire smoke is more toxic than an equal dose of ambient $PM_{2.5}$. Thus, residents in communities with a history of exposure to frequent wildfires are more likely to possess preconditions that weaken their respiratory system and/or immune system and thus increase their chances of becoming infected by COVID-19 (Prunicki et al., 2019; Isphording and Pestel, 2021; Magazzino et al., 2020; Naqvi et al., 2022). Furthermore, studies have demonstrated that even short-term exposure to wildfire smoke can exacerbate the probability and severity of COVID-19 infections and deaths (Deek, 2020; Travaglio et al., 2021).

In our paper, we argue that this relationship is intensified and exacerbated when the local community resources that are assigned to deal with both wildfires and COVID-19 are in high demand, but the provisions of such resources lag behind and/or are insufficient. There are several reasons for this. First, regarding hospital resources, large-scale wildfires (even without a raging pandemic) could force local hospitals to be closed or evacuated due to electricity failure, water shortages in buildings, damaged infrastructure or disrupted transportation systems for the transfer of patients (Hamideh et al., 2022; Melnychuk et al., 2022; Schranz et al., 2010). Wildfires can also rapidly increase the demand for health resources such as ventilators, medical services, and extra care for patients with severe COVID-19 symptoms (Ranney et al., 2020; Zangrillo et al., 2020). On the other hand, frontline medical workers are at a higher risk of becoming infected by COVID-19 patients whether due to a lack of personal protective equipment, burnout or extra workload, all of which impose additional challenges in the response to both wildfires and the COVID-19 pandemic (Gupta and Sahoo, 2020).

Second, with respect to public shelters and housing resources, wildfires could leave many people "homeless" (Goodling, 2019; Settembrino, 2017). In previous wildfire seasons, devastating wildfires in California forced more than one million people to evacuate between 2017 and 2019 (Wong et al., 2020). Public shelters and housing resources, whether intended for emergency use or not, are critical after natural disasters (Davlasheridze and Miao, 2021). In the case of wildfires, evacuation and/or sheltering in safe places can help residents decrease their chances of breathing in wildfire smoke (Cova et al., 2009; Whittaker et al., 2017; Wong et al., 2020a, 2021).

Unfortunately, a lack of access to stable shelter, infrastructure, and services means that the homeless community is exposed to a range of environmental hazards. Furthermore, the social vulnerability of local communities, as indicated by a high percentage of elderly people, young children, minorities, low-income households, and people living in nursing homes, among other indicators of vulnerability, can worsen COVID-19 outcomes in these communities (Cabral and Cuevas, 2020; Maxwell et al., 2020). Due to their inability to access adequate medical care, transportation, and nutrition, socially vulnerable populations face increased risks of health challenges during disasters (Karaye and Horney, 2020).

Based on these prior findings in the literature, we propose four hypotheses to answer the aforementioned questions regarding the concurrence of wildfires and the COVID-19 pandemic in California: (1) Wildfire smoke ($PM_{2.5}$) is positively associated with increases in COVID-19 infections and deaths. As wildfire smoke increases, increases in the availability of (2) hospital capacity and (3) public housing and related shelters, respectively, are associated with a decrease in COVID-19 infections and deaths. (4) Higher social vulnerability status exacerbates COVID-19 infections and deaths compared to lower social vulnerability status, whereas hospital and public housing resources moderate the effects of wildfires (wildfire smoke) on COVID-19 severity.

To test our hypotheses, we analyze data collected from multiple sources and employ a county-by-day panel fixed effects model. The model results show that wildfire smoke ($PM_{2.5}$) has a significant and positive effect on both COVID-19 infections and deaths. Moreover, by further limiting the number of ICU beds, wildfires in California have presented a challenge to local community health resources and worsened the COVID-19 outcomes of those communities. Although local communities have temporarily provided public housing resources – such as contracted hotel rooms to shelter the homeless – and have contained the spread of COVID-19, severe wildfires have also led to property losses. Once these residents have become homeless, they needed to utilize public housing resources. In this way, wildfires have exerted pressure on local public housing capacity and consequently exacerbated COVID-19 outcomes. Furthermore, the strain on the local health and housing infrastructures has been especially acute in counties experiencing high levels of social vulnerability.

3. Research methods

This study employs panel fixed effect models to examine the proposed hypotheses. Panel fixed effect models have the advantage of accounting for sources of unobserved heterogeneity, such as unobserved variation that could occur on a specific day in a given county, which our paper's empirical analysis exploits. As such, our unit of analysis is at the county-by-day level.

3.1. Data and variables

Data for the empirical analysis come from the State of California's COVID19.CA.GOV website, the California Department of Forestry and Fire Protection (CAL Fire), and the United States Environmental Protection Agency (EPA). Our research period is from April 1, 2020 to November 30, 2020. During this period, as the COVID-19 pandemic ensued 173 fire incidents were reported across 53 counties in California (with the exceptions of San Francisco, Inyo, Sutter, Del Norte and Alpine counties where no fires were reported), and the affected areas ranged from 69 acres to 1,395,881 acres.

Our sample includes a measure of wildfire smoke (represented by $PM_{2.5}$), available public shelters and housing units, available staffed ICU beds, and COVID-19 infections and deaths during the research period. These data are available on a daily basis for a majority of counties in the state of California. Of note, not all counties have provided public housing and shelter resources and the air quality monitoring system does not cover all counties nor report data on a daily basis. Excluding county-by-day cases with these missing data means that our final dataset is an unbalanced panel comprises of 5447 county-by-day observations for COVID-19 infections and 5357 county-by-day observations for COVID-19 deaths. Despite this, this study's sample is by and large representative of the state of California as a whole (see Table A in the supplementary materials).[1]

This study's outcome or dependent variables (DVs) of interest are COVID-19 infections and deaths. There are four key independent variables: (1) Consistent with other studies (Alman et al., 2016; Henderson, 2020; Reid et al., 2019), we use $PM_{2.5}$ to measure **wildfire smoke** and its impacts on human health. Following Miskell et al.'s (2019) approach, we have excluded counties with missing $PM_{2.5}$ data from our empirical analysis (as noted above). Details about COVID-19 infections and deaths, including attribution of fatalities to COVID-19 versus other causes, and information about the $PM_{2.5}$ data can be found in the supplementary materials. (2) **Hospital resource availability** is measured by the number of available staffed ICU beds per day at the county level (available ICU beds). (3) A**vailable public shelters and housing units** is measured by the number of shelters and temporary emergency housing units provided by local communities (e.g., hotel rooms or recreational vehicles, i.e., RVs). (4) **Social vulnerability** is measured by the 2018 CDC's social vulnerability index (SVI), and the lower and upper bound score on the SVI is 0 and 1, respectively.

Three variables are included to account for daily time-variant characteristics and county-level resources or policies:[2] (1) we employ a **fire indicator** (binary) to represent whether a county experienced wildfire on a given day (1 for yes, 0 for no fire incidents). (2) **Testing** is measured by the total number of people who receive COVID-19 tests in a county on a given day. (3) **Hospitalization** is measured by the number of patients currently hospitalized in an inpatient bed who have suspected or confirmed COVID-19 infections for each county on a given day. We include the latter two variables to preclude alternative explanations that link wildfire smoke to COVID-19 outcomes; they are expected to positively correlate with pandemic-related infections and deaths. Recent research shows that testing capacity can mask the COVID-19 infection rate (Omori et al., 2020; Sharfstein et al., 2020). Particularly for counties with limited testing capacity, reported cases may not reflect true epidemic growth.

Given the large data variability, a natural log-transformation was applied to COVID-19 infections, deaths, $PM_{2.5}$, hospital resource availability, public shelter availability, testing, hospitalization, and their interactions, which are denoted as lninfections, lndeaths, lnpm25, lnICU_beds, lnshelters, lntest, and lnhosp, and lnpm25Xlnshelters and lnpm25XlnICU_beds, respectively.

Table 1 presents summary statistics of the main variables of interest and the control variables for our sample frame. In this table, we also include descriptive statistics for the interaction terms of interest (i.e., lnpm25Xlnshelters and lnpm25XlnICU_beds) in our empirical analysis. Table B in the supplementary materials presents the correlations among the dependent variables, independent variables, and control variables as well as their interaction terms. The results show that lnhosp, lnshelters, and lnICU_beds are highly correlated. To thwart potential multicollinearity concerns (i.e., inflated standard errors), these variables appear in separate models (see model result tables) in our empirical analysis.

Table 1
Descriptive statistics (county-by-day dataset).

Variable	Obs	Mean	Std. Dev.	Min	Max
infections	14,152	9284.964	30289.320	0	431241
deaths	14,152	183.498	700.726	0	7977
shelters	7108	368.337	763.831	11	4697
$PM_{2.5}$	10,895	14.516	25.999	−1.3	692.300
hospitalization	14,152	88.343	271.294	0	2907
ICU_beds	12,885	56.770	149.714	−110	1502
fire_or_not	14,152	0.199	0.399	0	1
test	14,152	1769.950	5736.972	0	123257
lnpm25	10,858	2.148	0.927	−2.996	6.540
lninfections	14,002	6.634	2.761	0	12.974
lndeaths	11,183	3.373	2.137	0	8.984
lnhosp	10,792	3.160	1.896	0	7.975
lnICU_beds	11,475	2.828	1.600	0	7.315
lntest	14,152	9.855	2.360	1.609	15.965
lnshelters	7108	4.926	1.287	2.398	8.455
lnpm25Xlnshelters	6052	11.100	5.149	−8.054	39.282
lnpm25XlnICU_beds	9482	6.756	4.499	−12.215	30.058
Overall SVI	14,152	0.624	0.264	0.045	0.998
ratio_disadvantaged	14,152	0.357	0.254	0	1

3.2. Panel fixed effect modelling

Following a similar approach in other studies (e.g., Schwarz et al., 2022; Zhou et al., 2021), we model the COVID-19 outcomes (infections or deaths) of a county on a given day as follows:

$$COVID-19\ outcomes_{i,t} = \gamma_0 + \gamma_1 PM_{2.5\ i,t} + \gamma_2\ PM_{2.5} \times ICU\_beds_{i,t} + \gamma_3\ PM_{2.5} \times shelters_{i,t} + \gamma X_{i,t} + \alpha_i + fire\_or\_not_{i,t} + \mu_{i,t}$$

where i and t refer to the county and day, respectively. $PM_{2.5 i,t}$ represents the wildfire smoke in a given county on a given day and $X_{i,t}$ represents the county-level controls. Furthermore, γ_0 is the county fixed effect and α_i is the time (day) fixed effect. $fire\_or\_not_{i,t}$ is a binary variable indicating whether wildfire occurred in a county on a given day.

To analyze the indirect effects of wildfire smoke ($PM_{2.5}$) on COVID-19 infections and deaths through the moderating effects of local hospital and public shelter resources, we introduce, as mentioned above, the cross-terms of $PM_{2.5}$ with hospital capacity availability and public housing resources, respectively. In this context, $PM_{2.5} \times ICU\_beds_{i,t}$ represents the cross-term of $PM_{2.5}$ and hospital capacity of county i on day t, and $PM_{2.5} \times shelters_{i,t}$ represents the cross-term of $PM_{2.5}$ and public housing resources of county i on day t.

To examine the effect of social vulnerability on the relationship between wildfire smoke and COVID-19 infections and deaths, respectively, we create a dummy variable (svi_high) using the mean + 1 SD (i.e., standard deviation) of the overall SVI as a cutoff point for all California counties, following the approach of Biggs et al. (2021) and Freese et al. (2021). svi_high is recorded as 1 when a county's overall SVI score is higher than 0.8879; otherwise, this value is recorded as 0. There are 14 counties exhibiting a "high" level of social vulnerability. We use this dummy variable to conduct analysis on split samples of counties in California exhibiting high versus low social vulnerability (svi_high = 1, or 0), respectively.

4. Model results

Tables 2 and 3 report the panel fixed effect model results for COVID-19 infections and deaths, respectively. Presented in both tables are the results of three models corresponding to this study's first three hypotheses. Model 1 is a baseline model that includes the key independent variables ($PM_{2.5}$, ICU beds, and public shelters) and three control variables, namely, fire_or_not, testing, and hospitalization. Model 2 is the baseline model as well as the interaction term of wildfire smoke and available ICU beds in a county on a given day (lnpm25 × lnICU_bed). Model 3 is Model 1 along with an interaction term between wildfire smoke and available public shelters and housing units (lnpm25 × lnshelter).

Table 2 Model 1, which does not contain the interaction terms, shows that wildfire smoke has a significantly positive effect on COVID-19 infections. By contrast, we do not find a significant relationship between COVID-19 deaths and $PM_{2.5}$ when the interaction terms are excluded (see Table 3 Model 1). That being said, when the interaction term for wildfire smoke and public shelter resources enters into the model, as shown in Model 3 of Table 3, wildfire smoke exerts a statistically significant positive and direct effect on COVID-19 deaths.

Table 2
Daily panel fixed effect model results.

DV1 = lninfections	Model 1 (baseline)	Model 2 (ICU_beds)	Model 3 (shelters)
lnpm25	0.038*	0.106**	0.243***
	(0.022)	(0.049)	(0.089)
fire_or_not	−0.000	0.002	0.007
	(0.036)	(0.034)	(0.035)
lnICU_beds	−0.005	0.041	−0.009
	(0.031)	(0.041)	(0.030)
lnshelters	−0.074	−0.067	0.017
	(0.054)	(0.052)	(0.058)
lnhosp	0.248***	0.245***	0.241***
	(0.046)	(0.046)	(0.044)
lntest	0.757***	0.745***	0.738***
	(0.206)	(0.205)	(0.206)
lnpm25XlnICU_beds		−0.024*	
		(0.012)	
lnpm25Xlnshelters			−0.041**
			(0.016)
constant	−1.011	−1.059	−1.257
	(1.798)	(1.786)	(1.804)
day fixed effects	YES	YES	YES
county fixed effects	YES	YES	YES
r2	0.971	0.971	0.971
N	5447	5447	5447

*p < 0.1, **p < 0.05, ***p < 0.01. Robust SEs are included in parentheses.

Table 3
Daily panel fixed effect model results.

DV2 = lndeaths	Model 1 (baseline)	Model 2 (ICU_beds)	Model 3 (shelters)
lnpm25	0.026	0.158	0.525***
	(0.041)	(0.097)	(0.120)
fire_or_not	−0.001	0.003	0.016
	(0.069)	(0.067)	(0.064)
lnICU_beds	−0.038	0.050	−0.047
	(0.091)	(0.120)	(0.088)
lnshelters	−0.098	−0.087	0.117
	(0.093)	(0.091)	(0.096)
lnhosp	0.119*	0.112*	0.100
	(0.064)	(0.063)	(0.063)
lntest	1.187***	1.165***	1.139***
	(0.369)	(0.364)	(0.360)
lnpm25XlnICU_beds		−0.045*	
		(0.026)	
lnpm25Xlnshelters			−0.099***
			(0.024)
constant	−7.682**	−7.774**	−8.248**
	(3.345)	(3.310)	(3.196)
day fixed effects	YES	YES	YES
county fixed effects	YES	YES	YES
r2	0.860	0.862	0.866
N	5357.00	5357.00	5357.00

*p < 0.1, **p < 0.05, ***p < 0.01. Robust SEs are included in parentheses.

Turning to the results of the interaction terms, Model 2 results in Tables 2 and 3, respectively, show that the interaction of wildfire smoke and the availability of ICU bed has a significant and negative effect on both COVID-19 infections and deaths, at the $p < 0.10$ level. These results indicate that in areas with a higher density of wildfire smoke, an increase in hospital capacity availability is associated with a decrease in COVID-19 infections and deaths compared to areas that has a lower density of wildfire smoke. Based on our analysis, when $PM_{2.5}$ doubles, a one percent increase in hospital capacity reduces COVID-19 infections and deaths by 1.7 and 3.1 percent, respectively (see marginal impact calculations in the supplementary materials).

The results of Model 3 show that in the face of increased wildfire smoke, an increase in public shelters and housing resources is associated with a decrease in COVID-19 infections and deaths, at the levels of $p < 0.05$ and $p < 0.01$, respectively. A one percent increase in the availability of public shelters and housing resources is associated with a 2.9 and 6.8 percent reduction in COVID-19 infections and deaths, respectively, when $PM_{2.5}$ increases by two-folds (see marginal impact calculations in the supplementary materials).

Tables 4 and 5 compare the estimated coefficients of Models 1, 2, and 3 across the high and low social vulnerability groups of counties. Model 1 results in Table 4 show that wildfire smoke ($PM_{2.5}$) has statistically significant direct effects on COVID-19 infections for counties exhibiting low social vulnerability. After including its interaction effect with hospital resources in Model 2 of Table 4, the direct effect of wildfire smoke and its interaction effect with healthcare resources are significant for counties with both high and low overall SVI, respectively; there is no statistical difference between the two groups. In Model 3 of Table 4, after including its interaction effect with public housing and shelters, wildfire smoke has a significant direct effect and significant interaction effect on COVID-19 infections only for counties with a low overall SVI, while the effect for counties with a high SVI is nonsignificant.

Regarding COVID-19 deaths, the results in Model 1 of Table 5 indicate that wildfire smoke has no direct effect on COVID-19 outcomes for counties of both groups. After including its interaction effects with both hospital and public housing resources (as shown in Models 2 and 3 in Table 5), respectively, the direct and indirect effects of wildfire smoke on COVID-19 deaths are significant and positive for counties with both high and low SVI. That being said, the larger estimated coefficient for the high SVI group indicates a higher direct impact of increased $PM_{2.5}$ on COVID-19 deaths for areas experiencing higher versus lower social vulnerability (Model 2, Table 5), and the group difference is statistically significant at the 10 percent level. Likewise, the interaction effect between wildfire smoke and ICU beds exhibits a significant group difference with respect to COVID-19 deaths, with the high SVI group's estimated coefficient to be about four times larger than that of the low SVI group.

Taken together, Tables 4 and 5 results suggest that when a wildfire occurs in areas with a higher level of social vulnerability, an increase in the availability of staffed ICU beds is especially critical for reducing COVID-19 deaths. By contrast, hospital resources are critical in both counties with low and high levels of social vulnerability for curtailing COVID-19 infections.

5. Sensitivity analysis

Sensitivity analysis can help identify critical control points, prioritize additional data collection or research, and verify and validate a model (Christopher, Frey and Patil, 2002). We conduct sensitivity analysis in two ways to test the robustness of our findings. First, we construct an alternative measure of social vulnerability using the preliminary Climate and Economic Justice Screening Tool published by the White House's Council on Environmental Quality. This alternative measure is based on census tract-level climate and economic disadvantages.[3, 4] Since the state of being "disadvantaged" is calculated as a binary variable at the census tract level in the Climate and Economic Justice Screening Tool, to match our county-level analysis, we create an index variable of climate and economic disadvantages at the county level using the number of tracts within a county that is disadvantaged divided by the total number of tracts within a county. Therefore, whether a county is identified as disadvantaged or not depends on a ratio variable that varies from 0 (no tract is disadvantaged) to 1 (all tracts are disadvantaged).

We employ the same model specifications as in Tables 4 and 5 and use the same cutoff point strategy (mean + 1 SD) to perform subsample analysis. As such, ratio_disadvantaged_high is recorded as 1 when this value is higher than 0.6101, indicating counties that are more disadvantaged in terms of climate and economy; otherwise, this variable is recorded as 0. In this way, we have identified 13 counties that are highly disadvantaged (denoted as EJ ratio_high); among them, there are 7 counties that also exhibit a high overall SVI. Additional analyses conducted that follow the same subsample analysis approach validate our

Table 4
Panel fixed effect model results for counties with low and high levels of social vulnerability.

(DV1 = lninfections)	Model 1 (baseline)				Model 2 (icu_bed)				Model 3 (shelter)			
	Low SVI	High SVI	bo-b1	p value	Low SVI	High SVI	bo-b1	p value	Low SVI	High SVI	bo-b1	p value
lnpm25	0.052***	0.013	0.039	0.150	0.140***	0.047*	0.094	0.130	0.354***	0.027	0.327	0.060
	(7.010)	(0.79)			(10.99)	(1.91)			(15.37)	(0.73)		
fire_or_not	0.006	0.014	−0.009	0.450	0.004	0.019	−0.015	0.390	0.0104	0.015	−0.004	0.490
	(0.500)	(0.80)			(0.35)	(1.05)			(0.95)	(0.81)		
lnICU_beds	−0.040***	0.074***	−0.115	0.020	0.017*	0.102***	−0.085	0.170	−0.036***	0.073***	−0.109	0.030
	(-5.540)	(8.47)			(1.72)	(5.81)			(-5.05)	(8.23)		
lnshelters	−0.106***	−0.034**	−0.071	0.320	−0.096***	−0.030**	−0.066	0.340	0.015	−0.026	0.041	0.450
	(-7.740)	(-2.58)			(-7.03)	(-2.20)			(0.92)	(-1.17)		
lnhosp	0.258***	0.206***	0.052	0.320	0.252***	0.205***	0.046	0.340	0.244***	0.205***	0.039	0.260
	(32.150)	(14.21)			(31.44)	(14.14)			(30.85)	(13.96)		
lntest	0.704***	0.791***	−0.087	0.400	0.700***	0.788***	−0.088	0.470	0.714***	0.789***	−0.075	0.430
	(23.780)	(16.81)			(23.85)	(16.76)			(24.70)	(16.72)		
lnpm25XlnICU_beds					−0.030***	−0.012*	−0.018	0.240				
					(-8.46)	(-1.83)						
lnpm25Xlnshelters									−0.059***	−0.003	−0.056	0.070
									(-13.82)	(-0.43)		
constant	4.704***	3.655***	0.699	0.440	−0.603**	−1.210***	0.607	0.470	−1.106***	−1.164***	0.059	0.420
	(36.68)	(20.50)			(-2.26)	(-3.33)			(-4.15)	(-3.19)		
day fixed effects	YES	YES			YES	YES			YES	YES		
county fixed effects	YES	YES			YES	YES			YES	YES		
R2	0.969	0.982			0.970	0.982			0.970	0.982		
N	4156	1291			4156	1291			4156	1291		

*p < 0.1, **p < 0.05, ***p < 0.01. Robust SEs are included in parentheses.

Table 5
Panel fixed effect model results for counties with low and high levels of social vulnerability.

(DV2 = lndeaths)	Model 1 (baseline)				Model 2 (icu_bed)				Model 3 (shelter)			
	Low SVI	High SVI	bo-b1	p value	Low SVI	High SVI	bo-b1	p value	Low SVI	High SVI	bo-b1	p value
lnpm25	−0.008	−0.011	0.003	0.450	0.066***	0.269***	−0.203	0.070	0.427***	0.353***	0.073	0.430
	(-0.53)	(-0.42)			(2.65)	(7.14)			(9.48)	(6.04)		
fire_or_not	0.008	0.034	−0.026	0.470	0.006	0.073***	−0.067	0.360	0.012	0.041	−0.029	0.370
	(0.73)	(3.68)			(0.28)	(2.61)			(0.59)	(1.44)		
lnICU_beds	−0.132***	0.055***	−0.187	0.180	−0.085***	0.282***	−0.368	0.080	−0.127***	0.036**	−0.162	0.190
	(-9.52)	(3.89)			(-4.50)	(10.43)			(-9.24)	(2.54)		
lnshelters	−0.138***	−0.153***	0.016	0.470	−0.131***	−0.117***	−0.014	0.460	0.026	0.044	−0.017	0.490
	(-5.20)	(-7.20)			(-4.94)	(-5.61)			(0.86)	(1.24)		
Lnhosp	0.174***	−0.090***	0.264	0.050	0.168***	−0.101***	0.269	0.010	0.154***	−0.117***	0.271	0.000
	(11.21)	(-3.85)			(10.83)	(-4.47)			(9.99)	(-5.02)		
Lntest	0.315***	2.135***	−1.820	0.000	0.314***	2.116***	−1.801	0.000	0.335***	2.096***	−1.761	0.000
	(5.50)	(28.24)			(5.50)	(29.14)			(5.93)	(28.22)		
lnpm25XlnICU_beds					−0.025***	−0.102***	0.077	0.020				
					(-3.59)	(-9.70)						
lnpm25Xlnshelters									−0.084***	−0.081***	−0.003	0.450
									(-10.15)	(-6.88)		
constant	0.159	−14.06***	14.217	0.000	0.016	−14.59***	14.605	0.000	−0.797	−14.50***	13.699	0.010
	(0.30)	(-24.13)			(0.03)	(-25.95)			(-1.52)	(-25.24)		
day fixed effects	YES	YES			YES	YES			YES	YES		
county fixed effects	YES	YES			YES	YES			YES	YES		
R2	0.840	0.956			0.841	0.959			0.844	0.958		
N	4069	1288			4069	1288			4069	1288		

*p < 0.1, **p < 0.05, ***p < 0.01. Robust SEs are included in parentheses.

findings in the main analysis. By and large, sensitivity analyses that use the Climate and Economic Justice Screening Tool are consistent with findings in our main analysis (see Tables 6 and 7 in the supplementary materials).

Second, we construct a county-by-week panel dataset to verify whether the results of our county-by-day analysis hold at an aggregated level. An aggregated level of analysis allows for the accumulated effect of local communities' exposure to $PM_{2.5}$ from wildfire smoke. Following the approach in Chen et al. (2022), we convert the daily dataset into a weekly dataset using the mean value of a variable ($PM_{2.5}$) and by summing the values of variables (fire_or_not, available_ICU_beds, public shelters, hospitalization, total tests) within a 7-day frame. We employ the cumulative counts of COVID-19 infection and death counts every seventh day within the research timeframe as our two dependent variables. Extra analysis with weekly dataset shows that while the signs on the estimated coefficients are as expected, statistical significance is not always achieved (see Tables 8 and 9 in the supplementary materials).

6. Discussion and conclusions

This study examines the direct and indirect effects of wildfires on COVID-19 infections and deaths through the moderating impacts of hospital resources (as represented by available ICU beds) and public shelters and housing resources in local communities. The main findings of this study are as follows: First, during the 2020 wildfire season in California, when the COVID-19 pandemic was also raging, severe wildfire smoke represented by $PM_{2.5}$ is significantly associated with increases in COVID-19 infections and deaths, which could be a result of the compounded impact of wildfire smoke on the human respiratory system. This result is consistent with findings in medical science studies such as Zhou et al. (2021) and Cortes-Ramirez et al. (2022).

Second, wildfires have an indirect effect on COVID-19 infections and deaths by way of the availability of hospital resources. Providing more staffed ICU beds during the wildfire season reduced COVID-19 infections and deaths. Third, similarly, wildfires have an indirect effect on COVID-19 outcomes through the availability of public shelters and housing resources. Providing more shelters and housing resources to the public also reduced COVID-19 infections and deaths. Furthermore, both the direct effect of wildfire smoke and its indirect effects through interactions with hospital resources on COVID-19 outcomes (notably COVID-19 deaths) are more severe for communities that exhibit high social vulnerability or environmental disadvantages.

Our findings complement recent research that shows a link between community-level social vulnerability, policy interventions and capacity, and COVID-19 outcomes (Gupta and Sahoo, 2020; Karaca-Mandic et al., 2020; Qian and Jiang, 2022). Policy interventions, such as social distancing, availability of public shelters and staffed ICU beds are critical for reducing the severity of COVID-19 outcomes, and the provision of social assistance and professional medical aid is particularly urgent and in great demand in counties exhibiting high social vulnerability.

This study faces certain limitations. First, given data availability, we used panel data for only one state rather than for multiple states that have experienced both wildfires and the COVID-19 pandemic to test our hypotheses. As such, our findings may not be generalizable to other states or other emergency contexts, such as floods, droughts, and snowstorms. Second, we are unable to explicitly account for factors such as conditions of local emergency management staffing, budget, assets, and professional or administrative expertise that might affect the emergency management performance of local communities. That being said, assuming that these factors vary by time or county, we have accounted for them through day and county fixed effects. Third, findings on the robust checks indicate that our main model results are somewhat sensitive to sample size, with partial support for our hypotheses. We believe that the county-by-day analysis (our main analysis) provides the most appropriate level of analysis because it allows us to exploit daily variations in our DVs (COVID-19 infections and deaths) and main IVs (wildfire smoke and hospital and shelter resources) for a more statistically powerful estimation.

Despite the research limitations, this paper's findings have significant policy and management implications for local responses to future emergencies, which have become more frequent in the age of climate change, from wildfires to other natural disasters as well as to new variants of the COVID-19 virus and other types of rapid infectious diseases that will challenge local hospitals and housing resources. First, measures can be taken by public organizations to facilitate effective responses to the (co)occurrence or reoccurrence of different types of natural or human-made hazards. Increasing and expanding public shelters and temporary public housing through the use of contracted private hotels may be one direction for identifying appropriate measures to contain the spread of infectious diseases (e.g., mumps) and help wildfire evacuees shelter in safe places. Notably, beyond enhancing provision, answering the question of how to manage public housing resources appropriately to prevent outbreaks of infectious diseases in homeless service sites and shelters is critical to protecting already socially vulnerable groups.

Second, focusing on the provision and distribution issues related to hospital and healthcare resources could be another direction that health stakeholders and governments can take to prevent and mitigate the severe consequences of compound emergencies. On the one hand, as advocated by some clinical scholars (Dzierba et al., 2020; Melman et al., 2021; Supady et al., 2021), hospitals should develop emergency plans for situations in which medical resources and staffing cannot meet urgent needs. For example, how can scarce hospital resources be distributed in a balanced manner, and how can medical resources and scarce intensive care resources be allocated and managed to accommodate patients with different levels of COVID-19 symptoms and other diseases? How can medical resources and equipment, such as ventilators, be mobilized across different hospitals? To what extent can the variety and availability of health resources meet public needs in an emergency situation? These questions are currently being addressed and deserve more attention from hospitals and healthcare systems.

On the other hand, policymakers have the imperative to intervene when national emergencies and disasters occur and the market system alone cannot protect all citizens. Specifically, providing or mobilizing medical resources and equipment across the country, implementing policies to enforce stay-at-home orders and mask mandates, and providing economic assistance to individuals, families, small businesses, and hospitals are critical for reducing the impacts of COVID-19 and other infectious diseases (Miao et al., 2021; An et al., 2021; Bel et al., 2021; Dzigbede et al., 2020; Menifield and Clark, 2021).

Third, the differential impacts of wildfire smoke on COVID-19 outcomes across communities with high and low levels of social vulnerability suggest that environmental justice is a critical issue that needs to be addressed (Huang and London, 2012; Sadd et al., 2011; Thomas et al., 2020). In what ways can communities with low emergency response capacity protect their residents from the disproportionate impacts of various disasters, particularly when multiple disasters occur simultaneously? This is an important question that requires further investigation. Although challenges ensue, federal and local governments, in partnership with public and private sector entities, can help to narrow the gap between disaster needs and disaster service provision both nationwide and within specific localities.

Finally, although our paper confirms the findings of many environmental management studies (e.g., Contini and Costabile, 2020; Travaglio et al., 2021; Wu et al., 2020) concerning the direct effect of wildfire smoke on COVID-19 outcomes, previous research has not examined the moderating effects of hospital and housing resources in local communities during the wildfire season. Therefore, our findings also highlight the need for more research on the relationships between wildfires (and wildfire smoke) and COVID-19 outcomes in the context of other types of local responses, such as the disbursement of public and private funding resources to suppress wildfires and collaboration among multiple administrative units and with external private sector partners during emergencies. These investigations provide directions for our future research.

Credit author statement

Suyang Yu: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation and Visualization, Project administration, Writing – original draft, Writing – review & editing. Lily Hsueh: Conceptualization, Methodology, Software, Formal analysis, Investigation and Visualization, Resources, Validation, Writing – review & editing; Project administration, Supervision.

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Notes

1. Table A in the supplementary materials provides summary statistics on several key socioeconomic variables for the state of California (all 58 counties), this study's sample, and counties not in the study. When compared to all of California, this study's sample is not statistically different from the state as a whole. That being said, there are 14 counties that did not report $PM_{2.5}$ nor provid public shelters on a daily basis. These counties are Alpine, Amador, Colusa, El Dorado, Glenn, Inyo, Lassen, Mendocino, Modoc, Sierra, Tehama,

Trinity, Tuolumne, and Yuba. These are sparsely populated, rural counties with less diverse populations and experienced on average one to two more fire days in a given month compared to the California average and to the counties in this study's empirical analysis, respectively. Moreover, these counties on average recorded fewer COVID-19 infections and deaths during the 2020 wildfire season.

2. Aside from day and county fixed effects, we do not separately control for county-level differences over time in masking, sheltering-in-place or local policies (e.g., non-pharmaceutical interventions (NPIs) because by mid-June 2020 California Governor Gavin Newsom instituted a mask mandate in which he ordered all Californians to wear face covering while in public or high-risk settings (Source: https://twitter.com/GavinNewsom/status/1273696999066353664). While we are not able to fully capture the dynamic selection that could be happening due to differences in urban versus rural public attitudes or climate and political attitudes, California's state-wide mandate helps to allay the concern that wildfires might have led to migration into crowded areas, which increased COVID-19 transmission because of the exposure to the virus due to close proximity.
3. The White House's Climate and Economic Justice Screening Tool (CEJST) is in its beta version. It is used by President Joseph Biden's Justice40 Initiative and related programs across the federal government to identify disadvantaged communities. The CEJST is still evolving and likely to undergo changes. Source: https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5 (Retrieved September 12, 2022).
4. We also conduct a separate analysis using the COVID Community Vulnerability Index (CCVI) developed by Surgo Ventures (https://precisionforcovid.org/ccvi). Results based on the CCVI are very similar to our main model results. Analysis is available upon request from the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used in this paper are publicly available.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116918.

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