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Quantifying wildland fire resources deployed during the compound threat of COVID-19

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Fire agencies across the United States must make complex resource allocation decisions to manage wildfires using a national network of shared firefighting resources. Firefighters play a critical role in suppressing fires and protecting vulnerable communities. However, they are exposed to health and safety risks associated with fire, smoke inhalation, and infectious disease transmission. The COVID-19 pandemic further complicated these risks, prompting fire agencies to propose resource management adaptations to minimize COVID-19 exposure and transmission. It is unclear if and how the pandemic may have operationally influenced wildland firefighting personnel resource use given compounding wildfire and COVID-19 risks. Therefore, we developed generalized linear mixed models that were fit using multiple integrated datasets to detect changes in personnel resource use for years prior to and during the COVID-19 pandemic, while controlling for historical fire and landscape conditions, societal risks, and management objectives. Analyses of observed and predicted firefighting resource use revealed reductions in the mean personnel resources used per wildfire per day during the pandemic for models developed across the western U.S. and for various western U.S. fire regions. Notably, the Northern California and the Great Basin Coordination Centers showed statistically significant reductions in ground personnel use during the COVID-19 pandemic. Learning from wildland fire management strategies and resource use trends that occurred during the COVID-19 pandemic, fire agencies can better anticipate resource constraints that may arise during the compounding threats of severe wildland fire activity and infectious disease outbreaks to proactively prepare and adapt suppression management strategies.

From hurricanes to wildland fires, the co-occurrence of environmental hazards and the COVID-19 pandemic posed operational challenges to emergency and hazard management[1–6]. The dual threat of the COVID-19 pandemic and the severe 2020 and 2021 wildland fire years had the potential to strain an already strained and finite fire response workforce[1] who had to balance meeting operational wildland fire management objectives while mitigating disease transmission[2,3]. In addition to the exacerbated health risks faced by wildland firefighters[7], losing a portion of the workforce to illness or quarantine could have been a significant concern for wildland fire management, especially considering the potential for systemic resource deficits arising from sharing resources among multiple fires with COVID-19 outbreaks[8,9]. Thus, empirical understandings of wildland firefighting resource use over the course of the pandemic can reveal critical implications of compounding fire activity and pandemic threats, which may require adaptive wildland fire management strategies in a future characterized by increased environmental extremes and ongoing public health threats.

The structure and function of the wildland firefighting system presents unique challenges in mitigating COVID-19 risks. These challenges stem from several factors, including high-density working and living conditions, limitations on hygiene practices, exposure to wildfire smoke, and a highly transient workforce that can be deployed and reassigned to vast geographical areas throughout the United States[1,2,7]. Infectious diseases, including COVID-19, noroviruses, and "camp crud", can spread within and between fire crews and other hazard management personnel, particularly within wildland fire camps where hundreds to thousands of dispatched firefighters eat and sleep while deployed to fire incidents[8,10]. Fire camps may be "ideal settings" for infectious disease transmission, as exemplified during the 2011 Idaho Black Canyon Fire response, where approximately 27% of responders contracted a norovirus[11], and during the 2020 Colorado Cameron Peak Fire, where 76 positive

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COVID-19 cases lead to 273 quarantined personnel and two hospitalizations[9]. Evidence shows that firefighters had higher incidence rates of COVID-19 than surrounding communities[12]. Further, wildfire smoke exposure has been associated with an increased risk of COVID-19 infection and severity[7]. Infectious disease outbreaks—including but not limited to COVID-19—can threaten workforce health and safety, constraining critical resources and reducing the number of available firefighters[8,10]. As the wildland fire management sytem is interconnected as firefighters and other resources can be shared between fires and fire regions in quick succession, COVID-19 outbreaks have the potential to impact health and workforce capacity system-wide[8].

Fire agencies approached the 2020 fire season with limited knowledge of optimal management practices during epidemics or pandemics, yet recognized the potential threat of COVID-19 on firefighting operations. For instance, many (63%) wildland firefighters expressed that they were worried about COVID-19 hurting their fire agency's ability to function, as found through an international survey distributed to 38 countries (most participants from the U.S., Spain, and Italy) in 2020[13]. To mitigate the compounding risks of wildland fires and COVID-19, national and multi-jurisdiction fire management organizations proposed adapted wildfire management practices. Several guiding policy documents recommended changes to the wildland fire management paradigm[14]. The National Interagency Fire Center's (NIFC) *Wildland Fire Response Plan: COVID-19 Pandemic, for example,* outlined potential changes to fire suppression strategies, tactics, and resource use to minimize within crew COVID-19 transmission, including: (i) increasing remote work when possible, (ii) using "…suppression strategies that minimize the number of assigned personnel and incident duration"[15], pg. 16], and (iii) evaluating "…opportunities for the application of aviation and mechanized assets to reduce assigned personnel"[15], pg. 17]. The National Wildfire Coordinating Group (NWCG) also recommended the use of smaller spike camps to insulate crews and modules from one another to reduce exposure to other crews and the public (NWCG, 2022). These policy guidelines emphasized strategic and tactical approaches to mitigate COVID-19 exposure and transmission among personnel, particularly for firefighting and equipment crews (i.e., ground personnel).

Within the U.S. Incident Command System (ICS)—comprised of State and Federal land and emergency management personnel who respond to large fire incidents—the implications of the COVID-19 pandemic on firefighting resource availability is complex and challenging to assess, as daily personnel resource availability data are unavailable in part due to the complexities of the multi-jurisdictional U.S. wildland firefighter resource network[16]. In the absence of resource availability data, firefighting resource use trends were explored over the COVID-19 pandemic to identify potential correlations between firefighting personnel use and pandemic conditions. Hence, we ask:

- Across the western U.S., if and how did fire suppression ground personnel use per fire day differ during the COVID-19 pandemic relative to recent prior years?
- Did regional differences emerge regarding ground personnel resource use per fire day during the COVID-19 pandemic?

By investigating wildland firefighting resource use from 2017 through 2021, this work aims to shed light on if and how infectious disease outbreaks may be associated with wildland firefighting resource use changes. Firefighting resource use trends during the pandemic can support wildland firefighting planning, strategic operations, and decision-making in conditions of future communicable diseases emergence[17,18] and increasing wildland fire activity[19]. In the present analysis, ground personnel resource use was measured for each fire incident on a daily basis (herein, "fire days") and obtained from over 21,000 historical records of fire incidents and resource use data[20–22]. Considering the NIFC management guidelines and the potential for COVID-19 transmission, we hypothesized that during the COVID-19 pandemic (2020–2021), fewer ground personnel resources would be used per fire day than pre-COVID (2017–2019)[23]. During the study period, COVID-19 was a national risk and each U.S. fire region issued similar COVID-wildland fire management protocols; thus, we hypothesized that there would be no differences in ground resource use per fire day for different U.S. fire regions.

Generalized linear mixed models (GLMM) were developed to evaluate firefighting ground personnel resource use on a fire day basis from 2017 through 2021 across the western U.S. and for each of the seven western U.S. Geographic Area Coordination Centers (GACCs): Northern California (ONCC), Southern California (OSCC), Northwest (NWCC), Southwest (SWCC), Rocky Mountain (RMCC), Great Basin (GBCC), and Northern Rockies (NRCC). GACCs (herein, "fire regions") are spatially and operationally defined areas managed by multi-agency coordination groups, which prioritize incidents and allocate fire management resources regionally, and have unique cultures and priorities.

GLMMs assessed the correlational relationship between ground personnel resource use per fire day pre- and during-COVID years while controlling for weather and environmental conditions of the regional landscapes, fire characteristics, societal risks factors, and strategic objectives set by fire managers. Notably, the GLMMs aimed to control for regional and national fire activity and regional and national Preparedness Levels (PLs), which are categorical indicators of fire suppression resource availability dictated by fuel and weather conditions, fire activity, and committed suppression resources (Fig. 1)[22].

Results

Observed ground personnel resource use across the western U.S.

Table 1 shows the summary statistics of ground personnel used per fire day for the pre- and during-COVID fire day groups. Pre-COVID, the mean number of ground personnel used per fire day was 331 (SD = 653). During COVID, the mean ground personnel used per fire day decreased to 169 (SD = 285; Table 1). Despite the large standard deviations in ground personnel used per fire day, the large fire day sample sizes resulted in a high degree of accuracy in the estimates of the mean, as reflected in the small values of sample standard errors (SE

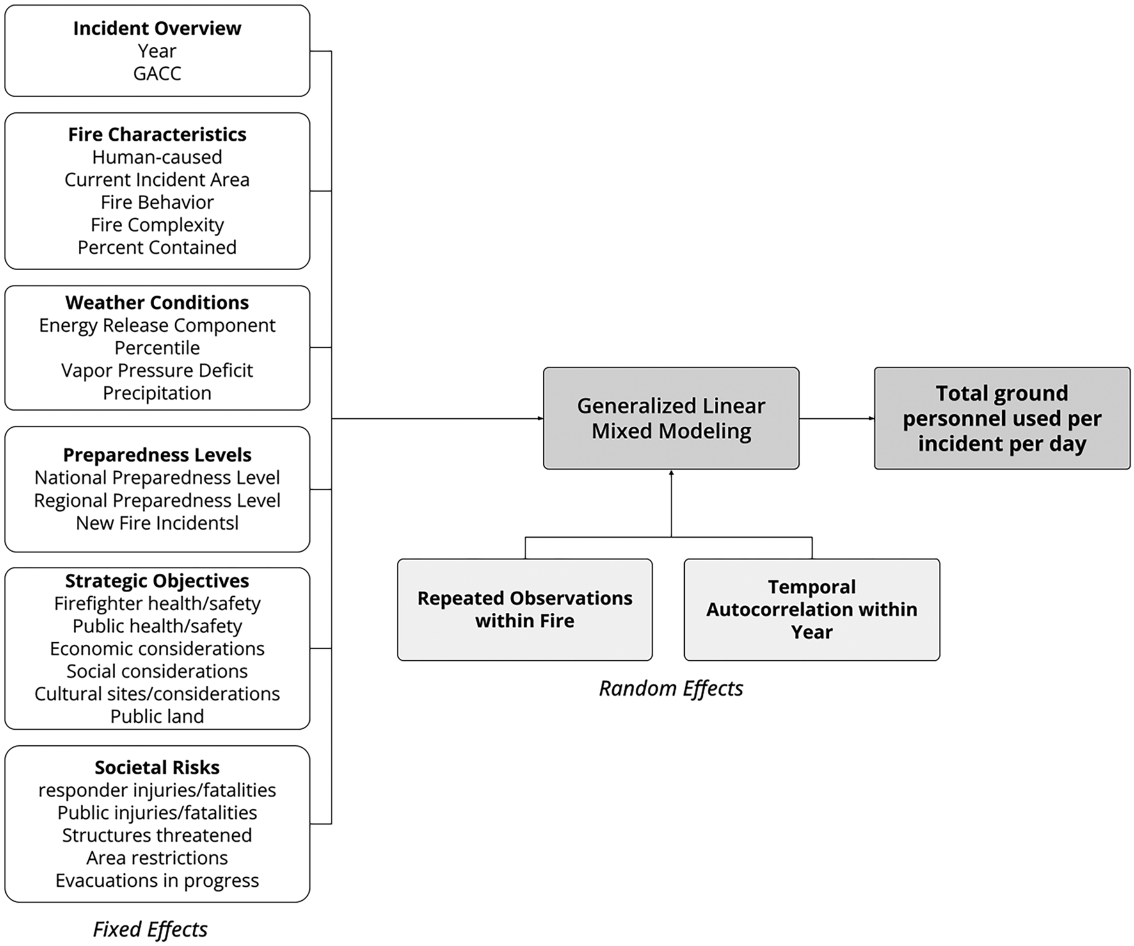

Figure 1. Conceptual framework illustrating model covariates and the predicted model outputs—ground personnel used per incident per day. The fixed effects covariates were included to control for fire characteristics, weather conditions, Preparedness Levels, strategic objectives, and societal risks on ground personnel resource use. Random effects included parameters for multiple fire day observations within a fire incident and a temporal autocorrelation within year.

		Ground personnel used per fire day			
Model subsample	***n* Fire days**	**Arithmetic mean (SD)**	**Geometric mean (SD)***	**Median**	**Mann–Whitney-Wilcoxon test**
Before COVID	10,679	331 (653)	93 (4)	126	$W = 6.8 \times 10^6$ ($p < 0.001$)
During-COVID	10,560	169 (285)	51 (5)	73	
Full sample	21,239	249 (511)	73 (6)	96	

Table 1. Descriptive and statistical hypothesis tests of ground personnel resource use per fire day for pre-COVID, during-COVID, and all 2017 through 2021 fire days. The null hypothesis for the Mann–Whitney-Wilcoxon test posited that the median ground personnel used/fire day were equal for pre- and during-COVID fire days, and the alternative hypothesis posited that the median ground personnel used/fire day during-COVID would be less than the pre-COVID mean and median. The model used a negative binomial link function, and therefore the regressors shared a multiplicative relationship with this predicted outcome. Hence, we included the arithmetic and geometric means in this table.

pre-COVID fire days = 4.3; SE during-COVID fire days = 2.7). Ground personnel use as aggregated over all fire incidents per calendar day and per fire acres burned per calendar day reflect similar reductions in ground personnel use during-COVID (Supplementary Fig. S2 online). A Mann–Whitney-Wilcoxon test (Table 1) found the during-COVID group had statistically significant ($p < 0.001$) lower ground personnel use per fire day, thus rejecting the null hypothesis that the pre- and during-COVID groups had equal ground personnel medians.

Figure 2 shows the relationship between total monthly fire acres burned and mean ground personnel used per fire day across U.S. fire incidents from 2017 through 2021. Generally, there was a positive association between monthly fire acres burned and mean ground personnel used such that as the monthly acres burned increases,

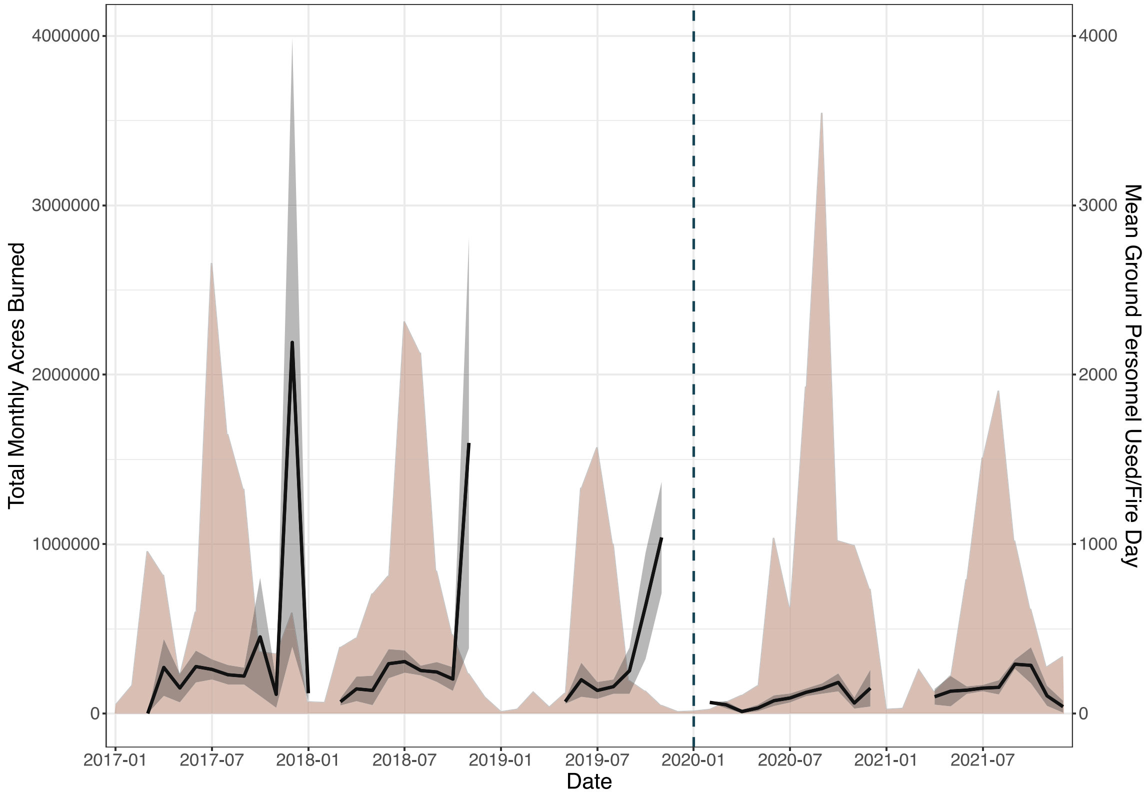

Figure 2. A timeseries trend of U.S. total monthly fire acres burned (orange shaded area) and mean ground personnel used per fire day (black lines with shaded standard deviations). Monthly fire acres burned were derived from monthly fire incident counts published by the National Centers for Environmental Information Fire History Data (NCEI, 2024) from January 2017 through December 2021.

as does mean daily ground personnel used per fire day within that month. However, this positive association plateaus such that the mean ground personnel used per fire day appears to decline, signaling potential resource availability constraints. Figure 2 shows that—especially in the spring into early summer of 2020—the mean ground personnel used per fire day was lower than prior years. Later into the 2020 fire year, when fire acres burned escalated, the mean ground personnel used per fire day increased, though not to the extent of ground personnel use in other years. The smaller mean ground personnel used per fire day in 2020 was likely associated with heightened fire acres burned, though the COVID-19 pandemic may have influenced ground personnel use, particularly when assessing January through June 2020.

Predicted ground personnel use across the western U.S.

GLMMs were developed to analyze if and to what extent ground personnel use decreased during-COVID per fire day controlling for fire size and behavior, national PLs, weather conditions, strategic objectives, and societal risk factor covariates (Fig. 1 and Supplementary Fig. S5 and Table S1 online). Annual results were used to compare ground personnel use for pre- and during-COVID fire days. A negative binomial link function was used in GLMMs due to the right skew of the ground personnel use outcome data (see Fig. S3-4 for histograms and empirical cumulative distribution functions).

Figure 3 shows the predicted mean ground personnel per fire day and corresponding approximate 95% confidence intervals across the western U.S. according to GLMMs, relative to the annual observed mean and median ground personnel per fire day (see Supplementary Fig. 7 online for residuals). In terms of predictive ability, the out-of-sample R^2 was 0.432 as tested on a random subsample of 20% ($n=241$ fire incidents). The out-of sample test was implemented by first fitting the GLMM to the other 80% of the data ($n=962$ fire incidents). The in-sample R^2 for this initial fit for the n = 962 incidents was 0.823 (see Supplementary Fig. S8 online). This fit is subsequently used to estimate parameter values and make predictions for the 241 withheld observations. Figure 3a,b shows the predicted and observed ground personnel per fire day for each (a) year and (b) for the pre- and during-COVID time periods across the western U.S according to the GLMM developed using the full sample ($n=21{,}239$). Figure 3a shows that there was a reduction in ground personnel used per fire day in 2020 relative to 2017 through 2019, particularly when comparing 2020 fire days to 2018 fire days.

Figure 3b shows comparative estimates for pre- and during-COVID time periods by averaging over the annual predicted ground personnel for pre-COVID (2017 through 2019) and during-COVID (2020 through 2021) fire days. Across the full western U.S. sample (n = 21,239), the GLMM predicted a reduction of approximately 55% of ground personnel used per pre-COVID (M = 162.6, SE = 50.5) relative to during-COVID (M = 73.5, SE = 22.2). See Supplementary Table S2 online for the full set of GLMM covariate estimates. Further, GLMMs were developed for

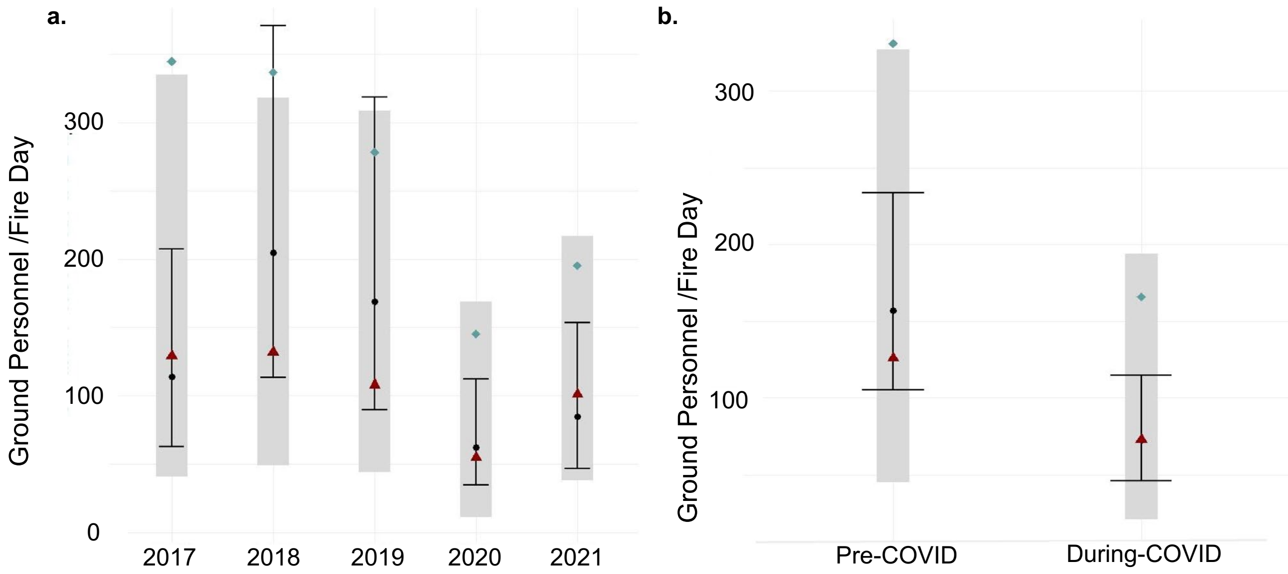

Figure 3. (**a**,**b**) Predicted and observed ground personnel used per fire day by (**a**) year and across the (**b**) pre-COVID (2017–2019) and during-COVID (2020–2021) time periods across the western U.S. The black boxplots show the predicted mean ground personnel per fire day and the approximate 95% confidence intervals around the mean for each year. The blue diamonds represent the observed mean, the red triangles represent the observed median ground personnel per fire day, and the gray bars show the observed interquartile range. For the pre- and during-COVID group comparison, the estimated mean ground personnel from the GLMMs was averaged over the respective years.

the following subsets of the western U.S. fire day data: peak fire season, non-peak fire season, excluding observations above the 90th percentile of ground personnel use, and for during-COVID (2020 through 2021) fire days. Ground personnel reductions during-COVID were consistent across these GLMMs, with results presented in Supplemental Table S3 and Fig. 9 online.

Observed ground personnel resource use by fire region

The observed arithmetic and geometric mean and median values for ground personnel used per day was greater pre-COVID than during-COVID for each of the seven western fire regions (Table 2). (See Supplemental Fig. 10 online for annual ground personnel use distributions per region). We observed the greatest mean ground personnel use reduction in Southern California (70%) and the Southwest (52%) and the least in the Northwest (19%)

	Ground personnel use per pre-COVID fire day				Ground personnel use per during-COVID fire day				
Fire Region (n total fire days)	**n Fire Days**	**Arithmetic Mean (SD)**	**Geom. Mean (SD)**	**Median**	**n Fire Days**	**Arithmetic Mean (SD)**	**Geom.Mean (SD)**	**Median**	**Mann–Whitney-Wilcoxon test**
Southern CA (n = 2628)	1512	766 (321)	253 (6)	344.5	1116	231 (282)	81 (7)	133.5	*p* < *0.001*
Southwest (n = 2037)	897	135 (156)	64 (4)	79	1140	65 (91)	23 (6)	37	*p* < *0.001*
Great Basin (n = 3002)	1607	136 (158)	59 (5)	89	1395	70 (102)	27 (5)	41	*p* < 0.001
Northern CA (n = 3038)	1582	783 (870)	361 (5)	443	1456	456 (559)	196 (5)	289	*p* < *0.001*
Northern Rockies (n = 3967)	1807	99 (105)	39 (6)	64	2160	65 (67)	27 (5)	41	*p* < *0.001*
Rocky Mountains (n = 1917)	1040	129 (156)	42 (7)	82	877	104 (146)	32 (6)	53	*P* < 0.001
Northwest (n = 4650)	2234	219 (244)	91 (5)	132	2416	178 (190)	81 (5)	122	*p* < *0.001*

Table 2. Observed fire day observations, arithmetic and geometric means (standard deviation), and median values for the ground personnel used per fire day pre-COVID and during-COVID for each fire region. The fire regions are ordered by the observed change in the arithmetic mean ground personnel use per fire day for pre-COVID to during-COVID fire days. The null hypothesis for the Mann–Whitney-Wilcoxon test posited that the median ground personnel used/fire day were equal for pre- and during-COVID fire days, and the alternative hypothesis posited that the median ground personnel used/fire day during-COVID would be less than the pre-COVID mean and median.

and Rocky Mountain (19%) regions. The Mann–Whitney-Wilcoxon tests (Table 2) show that the during-COVID group had significantly lower ground personnel use per fire day at the $\alpha < 0.001$ level for each fire region, rejecting the null hypothesis that there was no difference between pre- and during-COVID group ground personnel medians.

Predicted ground personnel use by fire region

We developed GLMMs for each of the western fire regions independently to assess regional changes in ground personnel resource use before and during the COVID-19 after controlling for region-level covariates. Figure 4a–g shows the observed and predicted mean ground personnel per fire day for pre- and during-COVID time periods, after averaging over pre-COVID (2017 through 2019) and during-COVID (2020 through 2021) estimates. Figure 4 orders fire regions according to their mean predicted percentage reduction in ground personnel used per fire day during-COVID, holding regional-level covariates constant. The region-specific GLMMs predicted lower mean ground personnel use during-COVID relative to pre-COVID for the Northern California, Rocky Mountain, Southwest, Great Basin, and Southern California regions. The mean predicted percentage reductions were statistically significant ($p < 0.05$) within (a) Northern California (from 976 to 252 ground personnel per fire day) and (d) the Great Basin (from 134 to 56 ground personnel per fire day). (See Supplemental Fig. S11 online for annual predicted and observed ground personnel use per fire day developed on region-specific GLMMs and find full model results in Supplemental Tables S5-S11 online). Conversely, the GLMMs predicted a during-COVID increasing trend in mean ground personnel use per fire day relative to pre-COVID for the (f) Northwest and (g) Northern Rockies regions, although these trends were not significant ($p > 0.05$).

Discussion

Prior to this study, the relationship between the COVID-19 pandemic and firefighting personnel use per fire day across the western U.S. was unknown. We used historical records of fire days from 2017 through 2021 to assess changes in ground personnel resource use between pre-COVID and during-COVID periods. Overall, we observed and predicted reductions in ground personnel use per fire day during-COVID relative to pre-COVID fire day observations across the western U.S. and within most western U.S. fire regions. These results signal that the COVID-19 pandemic may have influenced firefighting resource availability and use across much of the western U.S., with implications for wildland fire suppression management. Notably, however, the relationship

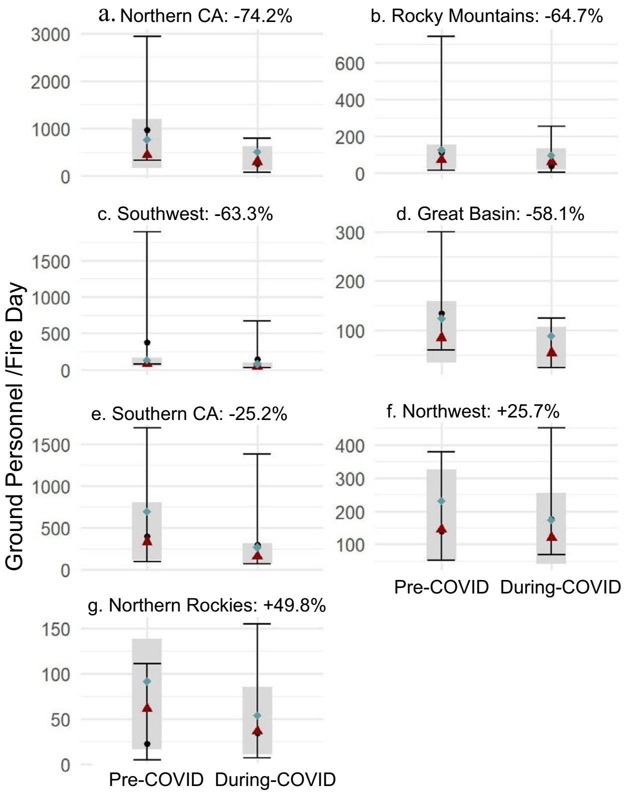

Figure 4. (**a**–**g**) Predicted ground personnel per fire day for each year according to GLMMs developed for each western fire region. The black boxplots show the predicted mean ground personnel per fire day and the approximate 95% confidence intervals around the mean for each year. The blue diamonds represent the observed mean, the red triangles represent the observed median ground personnel per fire day, and the gray bars show the observed interquartile range. The percentage change shown next to the name of each fire region reports the pre- to during-COVID change in the mean ground personnel used per fire day.

between the pandemic and ground personnel use should be interpreted as correlational rather than causal, especially considering the 2020 wildland fire activity that strained the supply of finite ground personnel resources, introducing resource availability and competition constraints.

Across the western U.S. and for each western U.S. fire region, the observed median values for ground personnel used per fire day during-COVID was significantly less than the median ground personnel used pre-COVID according to the Mann-Whitney-Wilcoxon tests (Tables 1 and 2). Further, aiming to account for seasonal variation and shifts in resource use within fire incidents, we developed GLMMs that controlled for fire characteristics, weather conditions, societal risk factors, strategic objectives of involved fire agencies, and regional and national PLs—a proxy for resource availability. At the western U.S. scale, GLMM results predicted that ground personnel use per fire day during-COVID reduced by an average of approximately 55% ($p < 0.01$) relative to pre-COVID fire days, while controlling for covariates.

Despite the potential toll of the COVID-19 pandemic on firefighting ground personnel use, we observed and our models predicted a marked *increase* in ground personnel resource used per fire day in 2021 to numbers near pre-COVID rates. Specifically, the predicted ground personnel resource used per fire day increased by approximately 134% from 2020 to 2021 (see Supplemental Fig. S9e online). This increase in ground personnel use per fire day in 2021 may be associated with the 2021 fire season being less severe in many fire regions[24]. While there were a few large, long duration fires (e.g., Dixie, Caldor, Monument, Marshall, Bootleg), ground personnel assignments may have increased in 2021 because of reduced resource competition and because the larger 2021 fires posed a high threat to communities. For instance, the Marshall Fire in Boulder County, Colorado was the most destructive Colorado fire in terms of buildings destroyed[25], and such societal risks may have required more aggressive suppression strategies. In addition to fluctuations in fire activity that our GLMMs aimed to control for, increased ground personnel use in 2021 may have been associated with lessons learned on wildland fire suppression management during COVID-19.

Regionally, there were observed ground personnel reductions during-COVID for all seven western fire regions (Table 2). In assessing whether this reduction persisted after controlling for covariates, region-specific GLMMs suggested statistically significant reductions in ground personnel used for the Northern California (from 976 to 252 ground personnel per fire day) and the Great Basin (from 134 to 56 ground personnel per fire day) regions. GLMMs for Northern California and the Great Basin predicted a reduction in mean ground personnel use by approximately 74.2% ($p < 0.01$) and 58.1% ($p < 0.05$), respectively, during-COVID fire days relative to pre-COVID fire days. Though not statistically significant, models predicted reductions in the mean ground personnel use per fire day during-COVID relative to pre-COVID fire days for the following regions: Rocky Mountain (-64.7%), Southwest (-63.3%), and Southern California (-25.2%). Comparative differences between regions affirm that it may be preferable to interpret results at the regional level, as resource use changes were disproportionate by fire region.

Though our models do not account for personnel agency affiliation (e.g., state, federal, contractors), potential ground personnel use reductions may be linked to resource availability factors such as the reduced availability of California inmate firefighting crews during the COVID-19 pandemic[26]. During the 2018–2019 fire year, CAL FIRE (California's state fire agency) reported that inmates composed approximately one-fourth of the total California firefighting workforce[26,27]; less than half of inmate firefighting crews were active for duty in the summer of 2020 due to COVID-19 transmission concerns–a reduction of over 1,000 wildland firefighters[28]. In July 2020, only 94 of the 192 state inmate crews were active, and thus the observed reduction in ground personnel use in California may have been in part attributed to the restricted availability of inmate crews[26]. Moreover, both Northern and Southern California had a very active fire season in 2020 with substantially higher numbers of uncontained large fires burning simultaneously than in 2017–2019 or 2021[29]. There were over 30 uncontained large fires burning simultaneously in California on 23 days in 2020, whereas in 2017–2019 and 2021, the maximum number of uncontained large fires ever observed on a single day was 16[29]. Thus, the reduction in ground personnel used per fire day in 2020 could have been related to resource scarcity due to the highly active fire season, though the regional GLMMs attempted to control for regional fire activity by including regional PLs and daily fire activity per region.

Resource use trends during the pandemic in the Southwest may be particularly insightful, as the Southwest consistently experiences a relatively early peak fire season for the U.S., coincidentally beginning at the same time as the COVID-19 pandemic in March 2020. The 2020 fire season in the Southwest was relatively active, burning nearly one million acres in Arizona alone – the states most active fire season in the past decade[30]. Future work exploring Southwest fire management perspectives and experiences in strategic and tactical operations at the start of the pandemic may be useful to inform whether observed and predicted ground personnel reductions were attributed to COVID-19 risk management concerns, resource availability, or potential data inconsistencies, considering that the Southwest's early fire season co-occurred during the start of the pandemic.

While the Northwest and Northern Rockies regions had observed reductions in ground personnel use per fire day during COVID, the GLMMs predicted increases in mean ground personnel used per fire day, likely attributed to above average regional fire severity in 2020. For instance, Washington state fires burned over 840,000 acres in 2020, exceeding Washington's 10-year average of approximately 330,000 acres burned annually[31]. Similarly, three of the ten largest wildfires in Oregon occurred in 2020 (e.g., Lionshead; Beachie Creek) and 2021 (e.g., Bootleg) compared to only one of the ten largest occurring in the pre-COVID period (e.g., the 2017 Chetco Bar fire).

In interpreting these findings, it is imperative to acknowledge that ground personnel use per fire day estimates are likely correlated with and constrained by the number of resources available on any given day. While the model attempted to control for resource competition and scarcity through the inclusion of regional and national PLs and daily regional fire activity, future inclusion of the total number of resources available for use per fire day would help clarify the relationship between resource availability and use. Though not yet reliably available at the federal scale, resource availability data would enhance understandings of if and how resource availability shifted during the COVID-19 pandemic[16]. Additionally, information on wildland firefighter COVID-19 or other illnesses prevalence could help clarify the relationship between infectious disease transmission and resource use on fire incidents; currently, such relationships have been modeled via epidemiological and agent-based models, though less so through field observations[8,10]. This information would support the current analyses on the correlation between infectious disease and potential reductions in wildland firefighting resource use by helping to untangle whether such reductions are associated with infectious disease transmission and/or whether reductions may be attributed to broader challenges across U.S. wildland fire management system, such as those involving workforce recruitment and retention, which has reduced the U.S. Forest Service personnel capacity over recent years[32,33]. Thus, GLMM results are correlational rather than causal, as various environmental, societal, political, and economic considerations not captured in the set of model covariates may influence ground personnel resource use per fire day.

Overall, current results indicate observed and predicted reductions in ground personnel resource use that correlated with during-COVID fire years, particularly in 2020; ground personnel use reductions remained after controlling daily fire characteristics, weather conditions, societal risks, strategic objectives, and Preparedness Levels. Whether due to strategic and/or tactical fire management approaches during the pandemic or reduced firefighting resource availability, it is critical to understand the magnitude and regions of resource use reductions, as operational efficiency may be compromised. Unpacking the relationship between resource use trends during pandemics can support fire agencies in better preparing for and adapting to the evolving fire landscape that will be met with future infectious disease risks, which are predicted to increase in frequency due to climate change[34].

Additionally, whether due to resource constraints posed by fire activity or by pandemics, reductions in firefighting personnel used per fire day may further strain the individual firefighter, who may be tasked with a greater workload. The increased workload facing the individual firefighter can in turn lead to fatigue, burn out, and attrition, all of which already challenge wildland fire agencies who face increasingly long fire seasons and fire severity, a trend attributed to climate change[35,36]. Further, disease severity is of concern; for instance, COVID-19 severity has shown to be exacerbated given wildfire smoke inhalation[7], and prior to COVID-19, wildland firefighters faced heightened respiratory illness transmission and severity[8,10]. Thus, it is vital to understand the compounding challenges and potential resource constraints faced by U.S. wildland fire management during epidemics and pandemics. Though correlational and likely influenced by the large and complex fires of 2020, the decline in ground personnel used per fire day during the COVID-19 pandemic suggests a need to prioritize and encourage adaptive management and preparation for a healthy and resilient wildland firefighting workforce.

Methods

Study design and data sources

Several data sources were integrated: (i) the Resource Ordering and Support System (ROSS) and the Interagency Resource Ordering Capability (IROC) databases for ground personnel use outcomes; (ii) the ICS-209 s for fire characteristics, strategic objectives, and societal risks; (iii) the NICC Incident Management Situation Report (IMSR) for PLs and fire activity; and (iv) GridMet for weather condition data (see Fig. S12 online). Data was collected, processed, and integrated for ICS-209 fire days that occurred between January 1, 2017 and December 31, 2021; thus, we used a fire day unit of analysis (n = 21,239 fire days). A global timeframe of 2017 – 2021 was selected because fire suppression heavy equipment (i.e., dozers, engines, helicopters, air tankers) capabilities and availability has been relatively consistent since 2017[37].

The United States is divided into 11 geographic fire regions that are defined by existing spatial operational areas, or Geographic Area Coordination Centers, which are used by the interagency fire management community. The selected fire regions share similar management structures based on their regional fire risks and resource allocation processes relative to regions that were not included here, the Alaska Interagency (AICC), the Eastern (EACC), and Southern (SACC) coordination centers[38]. Notably, California state includes two GACCS, the Northern California and Southern California Coordination Centers (ONCC and OSCC, respectively); both partner with the California Department of Forestry and Fire Protection (CAL FIRE), the largest state firefighting organization in the U.S., to provide Initial Attack dispatching for federal and state-owned aircraft.

Finally, data was cleaned and processed such that only wildland fires of fire Complexity Types 1, 2, or 3 were included. For the current analysis, we selected Complexity Types 1, 2, and 3 because fire managers generally report necessary ICS-209 data on a nearly daily basis to monitor incidents for large wildland fires of these complexity types[39]. We performed additional data cleaning to finalize the fire day sample for model results (see Supplementary Fig. S12 online). The analysis focused on fire day resource use, and we included a total of 21,239 fire day observations in the analysis, representing 1,916 unique fire incidents. Of these, 10,679 fire day observations occurred between January 1, 2017 and March 10, 2020, prior to the COVID-19 pandemic, and 10,560 fire day observations occurred between March 11, 2020 and December 31, 2021, during the COVID-19 pandemic. As there were no fire days that met the inclusion criteria in 2020 prior to March 10, fire days occurring in 2020 through 2021 in the model aligned with the definition of during-COVID fire days.

Variables

Table 3 includes the data sources and descriptive statistics of all variables included in this analysis. The ROSS/IROC databases were used for 2017 through 2021 ground personnel resource use per fire day data[21]. Ground personnel included fire crews and heavy equipment (i.e., fire engines, bulldozers) operators[16]. While the ROSS and IROC databases also contain information on overhead personnel used per fire day (i.e., those working in administration, logistics), we did not include these positions in our analysis due to the potential for remote work, and therefore overhead personnel may not have faced the same COVID-19 wildfire risks as ground personnel who could not work remotely. Thus, ground personnel resource use per fire day was the outcome of interest.

Variable Category (database)	Variable	Measure	Mean	SD	Median	25th Percentile	75th Percentile
Ground personnel resource use (ROSS/iROC)	Ground personnel used per fire day	Continuous	190.2	478.6	56	18	153
	Ground personnel used per fire day (log)	Continuous (log)	3.9	1.8	4.03	2.9	5.0
Incident overview (ICS-209)	During-COVID Threshold	Binary	0.5	0.5	0	0	1
	Human-caused	Binary	0.1	0.3	0	0	0
	Year	Factor					
Fire characteristics (ICS-209)	New fires in GACC	Continuous	16.4	15	13	7	22
	Complexity Type 1	Binary	0.2	0.4	0	0	0
	Complexity Type 2	Binary	0.3	0.4	0	0	1
	Complexity Type 3	Binary	0.5	0.5	0	0	1
	Current fire size (ha)	Continuous	33,395	81,797	5,444	956	26,354
	Current fire size (ha)	Continuous (log)	8.5	2.3	8.6	6.9	10.2
	Percent incident contained	Continuous	46.5	36	0.01	10	45
	Fire behavior: minimal	Binary	0.5	0.5	0	1	1
	Fire behavior: moderate	Binary	0.2	0.4	0	0	0
	Fire behavior: active	Binary	0.2	0.4	0	0	0
	Fire behavior: extreme	Binary	0.1	0.2	0	0	0
Weather conditions (GridMet)	Energy release component (percentile)	Continuous	0.8	0.2	0.9	0.8	0.9
	Daily accumulated precipitation (mm)	Continuous	0.6	2.9	0	0	0
	Vapor-pressure deficit (kPa)	Continuous	1.7	0.8	1.58	1.1	2.2
Societal risk factors (ICS-209)	Evacuations in progress or planned	Binary	0.04	0.2	0	0	0
	Area closure	Binary	0.01	0.1	0	0	0
	Structures threatened*	Continuous	405	3224	0.03	0.03	0.03
	Public injuries and fatalities	Continuous	2.1	5.8	0	0	0
	Responder injuries and fatalities	Continuous	0.1	0.9	0	0	0
Strategic objectives (ICS-209)	Historical, cultural concerns	Binary	0.2	0.4	0	0	0
	Public land ecological concerns	Binary	0.02	0.1	0	0	0
	Social considerations	Binary	0.2	0.4	0	0	0
	Economic considerations	Binary	0.1	0.3	0	0	0
	Personnel health and safety concerns	Binary	0.1	0.3	0	0	0
	Public health and safety concerns	Binary	0.2	0.4	0	0	0
Preparedness Levels (ISMR Reports)	PL 1 or 2	Binary	0.2	0.4	0	0	0
	PL 4 or 5	Binary	0.5	0.5	0	0	1
Daily COVID-19 caseloads (CDC)	New daily COVID-19 cases per state **	Continuous	2,077	3613	637	262	2712

Table 3. The variable categories, measurement types, mean, standard deviation (SD), median, and inter-quartile range (IQR) used for the set of model covariates. Data sources are listed in parentheses below the variable category, and more information on each datasource can be found online in Fig. S12. *Including residential, commercial, and other structure types; ** Only used COVID-19 caseloads in models that assessed 2020 versus 20.

Many covariates were collected from archived Federal Emergency Management Agency (FEMA) Incident Command System 209 Reports (ICS-209)[40]. For each day of a large fire incident, fire managers report and submit an ICS-209 to document and assess daily fire incident situations, including daily fire size and behavior, estimated societal risks, and strategic objectives for each incident per reporting period. Fire managers request and use fire suppression resources in part based on the suppression strategy selected. Suppression strategy decision-making is selected based on multiple objectives considered by fire managers[41,42]. Objectives include but are not limited to minimizing: health and human safety risks, social and/or political tensions, infrastructural damage, historical and/or cultural site damage, and ecological damage. Weighting schemes for incident objectives have been developed at the regional level to facilitate incident prioritization and suppression resource allocation decisions. Fire managers, such as Incident Commanders on IMTs, report on a near daily basis if and how these objectives may be achieved by suppression strategies and tactics. These reports support resource requests sent to regional Multi-agency Coordinating Group Systems (MACS), who make final resource prioritization and resource allocation decisions. To communicate if and how certain resources are needed to satisfy the multi-objective decision space of each fire incident, fire management fills out a narrative field in the FEMA ICS-209 report on a fire day basis. To capture strategic objectives, natural language processing (NLP) was used to deductively codify open-ended narrative fields in ICS-209 reports according to standard evaluation criteria used to determine incident priorities (NIFC, 2023) (see Supplementary Fig. S5 online). Thus, for each fire day, NLP helped integrate qualitative data related to the "harder-to-quantify" and intangible objectives that factor into incident prioritization and resource allocation decision making, including social, cultural, and political factors. Additionally, fire Complexity Levels were included and are categorical ratings of fire incident complexity that are determined by agency administrators on a fire day basis to facilitate personnel assignment decisions, as fire complexity indicates potential resource needs[39]. Complexity Types 1 are designated to the most complex fire incidents, and Complexity Types 5 are the least complex and most common.

Additional model covariates included regional and national PLs published daily within the NICC ISMRs. PLs reflect current and future fuel conditions, weather conditions, fire activity, and national resource availability[33]. Thus, PLs were used as model controls that serve as a proxy for national resource availability and scarcity and national/regional fire risk potential. For instance, a PL of 5 equates to the occurrence of 38 to 85 large wildland fires occurring nationally, requiring 14,000 to 20,000 personnel, or approximately 80% of U.S. Incident Management Teams (IMTs) and firefighting personnel[38]. A PL of 3 equates to the occurrence of 15 to 32 large wildland fire incidents, requiring 3,900 to 8,800 personnel. Additionally, model controls included the number of daily new fires per GACC to control for potential resource competition that can arise during concurrent regional fires.

In models assessing resource use for 2020 relative to 2021 fire days, daily statewide COVID-19 caseloads were included[43]. COVID-19 related covariates were included for the 2020 versus 2021 GLMM to better assess if and how shifts in ground personnel resource use in the pandemic were associated with fluctuations in the pandemic. Supplementary Table S12 online provides the covariate distributions in the pre-COVID and during-COVID subsamples, and Supplementary Table S13 and Fig. S11 show correlations between inputs and outcomes.

Model development and analysis

For statistical analyses of observed outcome data, we conducted inferential statistical tests to compare the observed median ground personnel use between the pre- and during-COVID groups. The non-parametric Mann–Whitney-Wilcoxon Rank Sum test was used to compare group medians without assuming normality in the ground personnel distribution.

Then, GLMMs were developed to assess the correlational relationship between the COVID-19 pandemic and trends in ground personnel resources used per fire day, controlling for fire size and behavior, weather conditions, regional and national PLs, strategic objectives, and societal risk factors as fixed effects for both the western U.S. and fire region models. (Fig. 1). The predictive GLMMs were fit using a negative binomial data model. GLMMs can accommodate non-continuous responses, such as count data, collected as repeated measures taken over time (i.e., repeated measures of ground personnel taken per fire day over the course of a fire incident). In this way, GLMM accounts for within- and across-fire variability, including both fixed and random effects[44,45]. Random effects included a parameter that accounted for fire day observations across each incident to capture the elapsed length of the fire incident. An Ornstein–Uhlenbeck covariance structure[46] for day of the season nested within year was included to account for temporal autocorrelation with irregular time points. A cubic B-spline[47,48] parameter was included to account for the day of the season to fit a non-linear relationship of ground personnel use throughout the summer.

We visually assessed model fit by plotting the fitted values against the observed values, residuals across time, and out-of-sample predictive ability (See Supplemental Fig. S8 online). We used the *glmmTMB* package[49] in the statistical software R to fit the model and the *tidyverse*[50] package to perform data manipulation. We assessed the effects of predictors using the packages *ggeffects*[51], *ggplot2*[50] and *emmeans*[52].

Results include statistics on the observed and predicted ground personnel use per fire day for pre- and during-COVID time periods across the western U.S. and for each of the seven western U.S. fire regions. GLMMs were developed (i) for the western U.S. and (ii) independently for each of the western U.S. fire region levels. Bar plots (Figs. 3 and 4) correspond to the predicted ground personnel used per year after back transforming ground personnel from the log scale. Then, we derived the mean pre- and during-COVID ground personnel estimates by averaging 2017–2019 annual estimates for pre-COVID fire days and 2020–2021 annual estimates for during-COVID fire days. For national and fire region models, estimates reveal the percentage change in the mean ground personnel used per fire day for during-COVID relative to pre-COVID fire days. Finally, we developed GLMMs that assessed ground personnel resource use for subsets of the data including fire days based on seasonality (i.e., peak and non-peak fire days) and COVID-19 pandemic progression (i.e., 2020 fire days relative to 2021 fire days) (See Supplemental Fig. S9 online for model results).

Conclusion

This study investigated the correlation between firefighting ground personnel resources used pre- relative to during the COVID-19 pandemic across fire regions in the western U.S. Using inferential statistics as well as generalized linear mixed models, results suggest a decrease in observed and predicted ground personnel resource use during the COVID-19 pandemic compared to pre-pandemic levels. While the full western U.S. analyses revealed reductions during the pandemic, the magnitude of reductions varied by fire region. Learning from wildland fire management strategies and resource use trends that occurred during the COVID-19 pandemic, fire agencies can better anticipate resource constraints and disruptions that may arise during the compounding threats of severe wildland fire activity and infectious disease outbreaks to proactively prepare and adapt suppression management strategies during future public health crises.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

E.M.W and E.B. conceptualized the research; E.M.W. and E.B. cleaned the data; E.M.W. and S.K. conducted data analysis; E.M.W. wrote the manuscript; E.B., M.S., and G.W.P revised the document and provided analytic feedback. All authors review the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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