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The Efficacy of Red Flag Warnings in Mitigating Human-Caused Wildfires across the Western United States

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ABSTRACT: Red flag warnings (RFWs) are issued by the U.S. National Weather Service to alert fire and emergency response agencies of weather conditions that are conducive to extreme wildfire growth. Distinct from most weather warnings that aim to reduce exposure to anticipated hazards, RFWs may also mitigate hazards by reducing the occurrence of new ignitions. We examined the efficacy of RFWs as a means of limiting human-caused wildfire ignitions. From 2006 to 2020, approximately 8% of wildfires across the western United States and 19% of large wildfires (≥40 ha) occurred on days with RFWs. Although the occurrence of both lightning- and human-caused wildfires was elevated on RFW days compared to adjacent days without RFWs, we found evidence that modification of short-term behavioral choices on RFW days may reduce the number of certain human-caused ignitions (e.g., debris burning). By contrast, there is limited historical evidence that RFWs reduce the number of ignitions caused by habitual behaviors (e.g., smoking) or infrastructure (e.g., power lines). Furthermore, the conditional probability of a human-caused wildfire becoming a large wildfire was 33% greater on days with RFWs, underscoring the value of wildfire prevention on these days. While RFWs are helpful in certain cases, our results suggest that their efficacy as a wildfire prevention measure has been somewhat limited in the western United States. As the biophysical wildfire potential and the density of people living in wildfire-prone areas increase, so do the benefits of improved wildfire early warning systems that complement other wildfire mitigation and adaptation efforts.

KEYWORDS: Emergency preparedness; Forest fires; Risk assessment

1. Introduction

Hazard warnings alert populations to conditions that may be dangerous and ideally encourage behaviors that mitigate risks. Certain weather-related hazard warnings, such as warnings of tropical storms, tornadoes, and extreme heat, are designed to reduce human exposure to and impacts from the hazard (Casteel 2016; Weyrich et al. 2018). Conversely, warnings of weather conducive to wildfires largely aim to inform land management and emergency response agencies of the potential for meteorological conditions to drive the growth of active fires and to enable new ignitions. When such warnings are shared with the general public, they may also mitigate a major driver of the hazard: ignitions caused by human activity (McCaffrey et al. 2020; Syphard and Keeley 2015). Warnings about wildfire hazards are increasingly relevant given that approximately half of the global human population lives in areas that overlap with wildland vegetation (the wildland–urban interface) (Schug et al. 2023) and humans are responsible for most wildfire ignitions in many regions (e.g., 84% of wildfire ignitions in the United States; Balch et al. 2017). Although lightning-caused wildfires often become larger than human-caused wildfires and are associated with the majority of burned areas in the western United States (Abatzoglou et al. 2016), human-caused wildfires tend to be more destructive because they are more likely to occur near human settlements (Higuera et al. 2023). Moreover, in some regions, human-caused wildfires are more likely than lightning-caused wildfires to occur during extreme fire weather conditions (e.g., strong dry winds), which increase the rate of expansion of wildfires (Hantson et al. 2022).

In the United States, weather forecast offices (WFOs) of the National Weather Service issue red flag warnings (RFWs) on the basis of forecasted fire weather conditions capable of supporting numerous new ignitions and contributing to extreme fire behavior or rapid expansion of existing wildfires. Fire weather conditions generally refer to the coincidence of high winds, low relative humidity, high temperature, and dry vegetation. Each weather forecast office develops its own criteria for issuing RFWs in collaboration with fire and land management agencies, and RFW criteria can vary across a weather forecast office's fire weather zones—areas within which weather, topography, and vegetation are similar (National Wildfire Coordinating Group 2023). Criteria for issuing an RFW may also change over time. For example, changes to relative humidity criteria in Colorado were recommended following a wildfire in 2021 that caused record economic losses. A burn ban was issued, but no RFW was issued on the day that fire ignited (Benjamin et al. 2023).

RFWs are primarily intended as alerts to land management agencies to escalate fire suppression response, resource allocation, or emergency management strategies. However, when released in National Weather Service bulletins, announced

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via smartphone apps or in the media (Vélez et al. 2017), or included in other messaging by agencies, RFWs can additionally alert the public to exercise extreme caution with any activities that could ignite a wildfire, potentially increasing situational awareness. Although most fires are small and not consequential, the four wildfires in the western United States that caused the greatest number of human fatalities occurred during RFWs and were associated with potentially preventable human-caused ignitions (Camp Fire in 2018, Oakland Hills Fire in 1991, Tubbs Fire in 2017, and Cedar Fire in 2003). Although RFWs were not designed for public messaging on fire prevention, such warnings offer the potential to mitigate fire risk by limiting the number of new ignitions. In the United States and globally, hazard forecasters are being encouraged to incorporate information about the potential consequences of the hazard into their warnings (Merz et al. 2020; Uccellini and Ten Hoeve 2019). Some research studies suggest that coupling hazard warnings with behavioral recommendations generally is more effective than solely addressing weather conditions (Potter et al. 2018) or weather conditions and potential impacts (Weyrich et al. 2018). However, evidence is ambiguous that warnings of extreme weather, with or without information about possible impacts and avoidance or preparedness actions, change human behavior and improve outcomes (McLoughlin et al. 2023; Sheridan 2007; Weinberger et al. 2018). In part, these uncertainties reflect the limited capacity for research on relations among meteorology, sociology, and behavioral decisions (National Academies of Sciences, Engineering, and Medicine 2018).

In the western United States, human-caused wildfires occur across more extensive geographic ranges and seasons than lightning-caused wildfires (Balch et al. 2017), many of which are preventable in the presence of targeted wildfire prevention strategies. The Fire Program Analysis Fire-Occurrence Database (Short 2014), the most comprehensive source of data on wildfire ignitions across the United States, classifies causes as natural or lightning-caused (hereafter, natural); arson or incendiarism (hereafter, arson); debris and open burning (hereafter, debris burning); equipment and vehicle use (hereafter, equipment); firearms and explosives use (hereafter, firearms); fireworks; misuse of fire by a minor (hereafter, minor); power generation, transmission, or distribution (hereafter, power); railroad operations and maintenance (hereafter, railroad); recreation and ceremony (hereafter, recreation); smoking; other causes; and missing data, not specified, or undetermined (hereafter, missing). Some of these causes generally reflect short-term behavioral decisions, whereas others are linked to contemporary infrastructure, social norms, and habitual behaviors (Butry et al. 2010). Similarly, patterns of ignition causes vary seasonally, geographically, and across fire potential metrics (Grala et al. 2017; Sjöström and Granström 2023; Vachula et al. 2023). Relatively little is known about how these patterns of ignition relate to the issuance of RFWs. Closing this gap is crucial as understanding of factors that affect the probabilities of wildfires with different causes (Brey et al. 2018; Jenkins et al. 2023; Zhang and Lim 2019) increases the ability to mitigate human-caused ignitions (Prestemon et al. 2010).

We aimed to quantify the potential efficacy of RFWs in mitigating human-caused fire ignitions. Others have examined the outcomes of different wildfire prevention strategies, including technological advances, education, and policies (Hesseln 2018), but to our knowledge, studies have not evaluated the extent to which RFWs contribute to fire prevention. We assessed whether the number of wildfires ignited by different causes across the western United States from 2006 to 2020, as well as the conditional probability of those wildfires becoming large, was associated with the issuance of RFWs. We note that RFWs occur on days with extreme fire weather, confounding the ability to use case-control analyses to directly examine their effectiveness. Instead, we tested whether the percentage of wildfires and large wildfires, by cause, differed between days when RFWs were in effect and proximate days when RFWs were not in effect.

2. Methods

a. Data

We obtained records of RFWs from 2006 to 2020 across the western United States (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming) from the Iowa Environmental Mesonet (mesonet.agron.iastate.edu/archive/). For each RFW, we recorded the fire weather zone, issuing weather forecast office, and initial issuance and final expiration date. If an RFW was in effect for any part of a calendar day, we classified the day as one with an active RFW (Clark et al. 2020). The boundaries of some fire weather zones changed during the study period. To account for these changes, we mapped RFWs to fire weather zone boundaries as of 2020. In the small number of cases in which the previous fire weather zone covered less than a third of the current zone, we omitted the RFW from the analysis. Our unit of analysis is an RFW within a fire weather zone. Therefore, we treat a single RFW that encompasses multiple fire weather zones as multiple RFWs, each applicable to a distinct fire weather zone.

Some weather forecast offices may issue RFWs when lightning occurs coincident with limited precipitation and dry fuels. However, the criteria for each of the RFWs in our data were not available. Given our interest in identifying RFWs that were issued in the absence of lightning due to our focus on preventable human-ignited fires, we calculated the daily cloud-to-ground lightning density for each fire weather zone from the National Lightning Detection Network. Although such observations are inherently different from forecasts of dry lightning (Nauslar et al. 2013), we used the occurrence of lightning as a proxy to discriminate between RFWs with lightning ($\mathrm{RFW}_{\mathrm{lightning}}$) and RFWs without lightning ($\mathrm{RFW}_{\mathrm{nolightning}}$). We classified an RFW as without lightning if the density of lightning was <0.001 strikes km^{-2}.

We obtained data on the location, discovery date, final size (area within the perimeter), and cause of wildfires from the Fire Program Analysis fire-occurrence database (Short 2014, 2022). We classified a subset of human causes as amenable to management through behavior (elastic: debris and open burning, firearms and explosives use, fireworks, and recreation and ceremony) or associated with infrastructure and habit (inelastic: arson or incendiarism; equipment and vehicle use; misuse of fire by a minor; power generation, transmission, or distribution; railroad operations and maintenance; and smoking). For example, the method by which smokers choose to dispose of their cigarette butts rarely reflects conscious decisions, and clinical characteristics of minors who play with fire are different from those who do not (Sasaki et al. 2023). Although the classification of ignition causes as elastic or inelastic is subjective and does not account for all contexts (e.g., certain ceremonial uses of fire are not elastic), it allows us to identify some similarities in the conditions associated with different ignition sources. Also, we classify energy distribution as inelastic but acknowledge that some utilities recently began to proactively de-energize power lines during extreme fire weather conditions to limit the potential for ignitions.

Surface meteorological data from gridMET (Abatzoglou 2013) were used to examine fire weather metrics. We specifically used 100-h dead fuel moisture calculated from gridMET through the U.S. National Fire Danger Rating System (Cohen and Deeming 1985), daily mean 10-m wind speed, and daily mean vapor pressure deficit. These surface fire weather metrics were spatially averaged across the extent of fire weather zones.

b. *Analyses*

We calculated the total number of RFWs and the average annual number of days on which RFWs were active for the 432 fire weather zones within 31 weather forecast offices across the western United States. We characterized the seasonality of RFWs across the western United States to describe where and when RFWs occur. Within each fire weather zone, we summed the number of RFWs during each calendar month over all years and then calculated the average percentage of RFWs issued in each month relative to the total number of RFWs. We then applied k-means clustering to group fire weather zones with similar monthly average percentages across the 12 months. We also calculated the percentage of ignitions discovered on RFW days and the percentage of those ignitions that resulted in large fires (≥40 ha), by cause.

To better determine the percentage of fires ignited by each cause on RFW days relative to days without RFWs, we developed pseudocounterfactuals. In developing pseudocounterfactuals, we acknowledge that there is no true counterfactual for RFW days given that the issuance of RFWs is dependent on fire weather conditions that meet explicit criteria. Pseudocounterfactuals mirror case-crossover designs in epidemiological studies (Maclure 1991) that compare acute events—here RFW days—to adjacent windows of time that are at least two but not more than 3 days from the event. We excluded the day prior to and immediately following RFW days from our pseudocounterfactuals due to potential lags in the discovery of wildfires [e.g., holdover lightning-caused wildfires (Schultz et al. 2019)]. For example, the pseudocounterfactual days for RFW days on 4–5 September were 1–2 and 7–8 September. However, if those pseudocounterfactual days were RFW days or fell within 1 day of an RFW day, we excluded them. Selecting days adjacent to RFWs as pseudocounterfactuals allowed us to emulate the seasonality of RFWs and the moderate-term environmental conditions on RFW days, such as longer-lived fuel moisture, but without the forecasted weather (e.g., strong winds, low humidity) that likely was the basis for issuing an RFW. This process yielded a similar number of pseudocounterfactual and RFW days. A comparison at the fire weather zone level indicated that on RFW days, average daily wind speeds were 0.3 m s^{-1} higher (averaged across fire weather zones), 100-h dead fuel moisture was 1.2% lower, and vapor pressure deficits were comparable to those on pseudocounterfactual days.

To assess whether RFWs were associated with differences in the proportion of human-caused ignitions, we compared the average number of ignitions per day, by cause, on RFW and pseudocounterfactual days. We also compared ignitions on RFW days with lightning (fire weather zone lightning density $\geq$ 0.001 strikes km^{-2}) and RFW days without lightning. Because RFWs are defined at the fire weather zone level, we used pseudocounterfactuals from the same fire weather zones to ensure proper sampling statistics. However, we present results aggregated at the level of weather forecast offices (all RFWs across all fire weather zones within the office's jurisdiction) and the western United States (all RFWs across all weather forecast offices in the western United States). To assess whether differences in the average number of ignitions per day between RFW and pseudocounterfactual days were statistically significant, we resampled RFW days (n = 1000) and their pseudocounterfactual days, with replacement. We set statistical significance at $p \leq 0.05$ (i.e., the 95% confidence interval of the sample did not include zero difference), and hereafter, we use significant to denote differences at $p \leq 0.05$. At the resolution of the western United States, we examined all ignition causes individually. At the level of weather forecast offices, given limited sample sizes, we classified ignition causes as natural, inelastic human-caused, or elastic human-caused.

To complement our analysis of the daily number of ignitions, we compared the conditional probability that an ignition on an RFW day and a pseudocounterfactual day became a large (≥40 ha) wildfire. Although wildfires may not reach this size threshold until several days after the discovery date, fire weather coincident with ignition and other factors contribute to the probability that an ignition becomes a large wildfire (Abatzoglou et al. 2018a; Rodrigues et al. 2019). We calculated the conditional probability of large wildfires as the ratio of large wildfires ignited on RFW days to the total number of fires ignited on RFW days. We used the resampling method described above to compare the conditional probability of large wildfires on RFW days to that on pseudocounterfactual days and to assess whether differences were statistically significant.

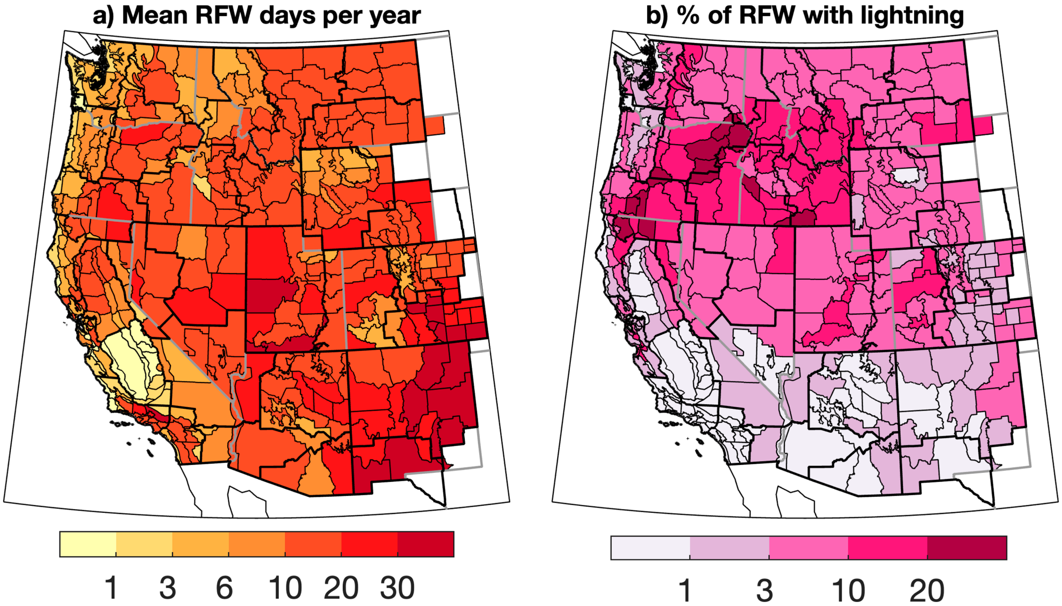

FIG. 1. (a) Average annual number of days from 2006 to 2020 on which RFWs were active within each National Weather Service fire weather zone. Bold black lines indicate the boundaries of WFOs. (b) Percentage of days with RFWs where daily cloud-to-ground lightning density across the fire weather zone was ≥0.001 strikes km^{-2}. These days are characterized as RFW days with lightning in the manuscript.

3. Results

a. *Distribution of red flag warnings*

From 2006 through 2020, at the resolution of fire weather zones, the National Weather Service issued 41 400 RFWs across the western United States. Averaged across fire weather zones, RFWs occurred on approximately 10 days yr^{-1}. The average annual number of days on which RFWs were issued generally was greatest in inland fire weather zones, especially those in western Utah, eastern New Mexico, and southeastern Colorado, which averaged over 30 RFW days per year (Fig. 1a). Relatively few RFWs were issued for fire weather zones in the San Joaquin Valley, California, which is dominated by irrigated agriculture, and along the Pacific coast from central California to Washington, where large fires are rare. Lightning co-occurred with RFWs on approximately 5% of RFW days across the western United States, with the greatest relative occurrence of RFW days with lightning across the Great Basin and in the interior northwestern United States (Fig. 1b).

The seasonality of RFWs varied geographically. The *k*-means clustering suggested four distinct and mostly contiguous clusters (Fig. 2), which can be associated with regional climate. In the north cluster (Washington, Oregon, Idaho, Montana, and Wyoming), the number of RFWs peaked during summer when low fuel moisture and widespread dry lightning coincide. In the south cluster (primarily southeastern California, Arizona, New Mexico, and southern and eastern Colorado), most RFWs were issued in spring, coinciding with dry fuels and high winds prior to the onset of monsoon rain. In this cluster, few RFWs were issued during the July–August monsoon season. In the California cluster (western California from the Sierra Nevada south to the Peninsular Ranges and west to the coast), most RFWs were issued in late summer and early autumn, coinciding with seasonally dry fuels and strong offshore, downslope winds (Abatzoglou et al. 2021; Zigner et al. 2022). In the central cluster (Great Basin and western Colorado), the number of RFWs peaked in late spring and early summer when winds can be gusty and in early autumn when fuel moisture is still low.

During the 15-yr study period, 8% of all wildfires, including 19% of those ignited by natural causes (lightning) and 8% of those ignited by humans, were discovered on days with RFWs (Fig. 3). Twenty-two percent of wildfires with final sizes ≥40 ha were discovered on RFW days (Fig. 3). The percentage of fires caused by distinct human causes concurrent with RFWs varied from 14% (power generation, transmission, or distribution) to 5% (debris and open burning). These percentages exceeded the 2.8% of days per year on which RFWs were in effect, indicating a relative increase in ignitions from all causes on RFW days.

b. *Number of ignitions on days with red flag warnings and pseudocounterfactual days*

Across the western United States, the number of wildfire ignitions was 77% higher on days with RFWs than on pseudocounterfactual days. However, differences in the number of wildfires on RFW and pseudocounterfactual days varied among ignition causes, particularly when grouped by days without or with lightning (Fig. 4).

On RFW days without lightning, the number of fires ignited by most human causes was significantly greater than on

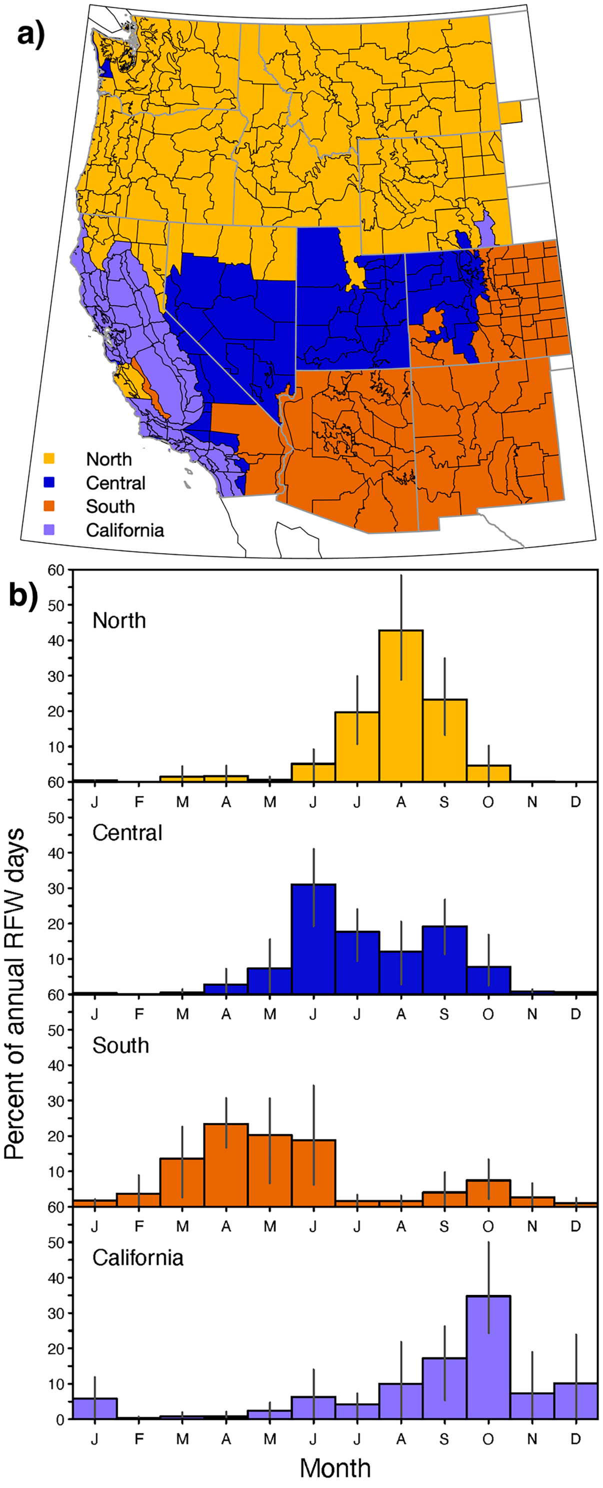

FIG. 2. (a) Fire weather zones clustered on the basis of the seasonality of RFWs from 2006 to 2020. (b) Mean annual percentage of days on which RFWs were active during each month in each cluster. Vertical lines for each month depict the 0.15–0.85 percentiles pooled over fire weather zones in each cluster.

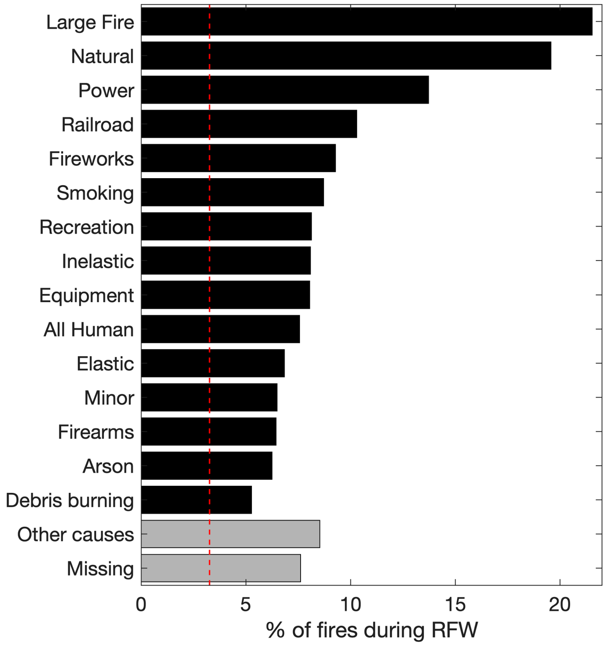

FIG. 3. Percentage of wildfire causes, groups of fire causes, and large fires (≥40 ha) in the western United States from 2006 to 2020 that were discovered on days on which an RFW was in effect in the fire weather zone corresponding to the ignition location. Elastic causes include debris burning, firearms, fireworks, and recreation. Inelastic causes include arson, equipment, minor, power, railroad, and smoking. The dashed red line shows the average percentage of days with RFWs across the western United States.

pseudocounterfactual days (Fig. 4): power generation, transmission, or distribution (+120%); smoking (+65%); railroad operations and maintenance (+54%); equipment and vehicle use (+31%); misuse of fire by a minor (+31%); arson or incendiarism (+21%); recreation and ceremony (+19%); and debris and open burning (+13%). Effect sizes generally were greater among ignitions with inelastic human causes (+41%) than elastic human causes (+13%). The number of ignitions that became large wildfires was also significantly greater (+129%) on RFW days without lightning than on pseudocounterfactual days without lightning.

On RFW days with lightning, not surprisingly, lightning-caused (natural) fires were over 500% more likely than on pseudocounterfactual days. Similarly, as lightning-caused fires are often larger than human-caused fires, large fires were 375% more likely to occur on RFW days with lightning than on pseudocounterfactual days. Although the total number of human-caused fires was not significantly different on RFW days with lightning than on pseudocounterfactual days (−5%), the number of human-caused fires ignited by some activities, including recreation and ceremony (−20%), was significantly lower than on pseudocounterfactual days.

At the level of weather forecast offices, results were similar (Fig. 5). Across weather forecast offices, the number of fires ignited by elastic human causes was not significantly different between RFW and pseudocounterfactual days except in the

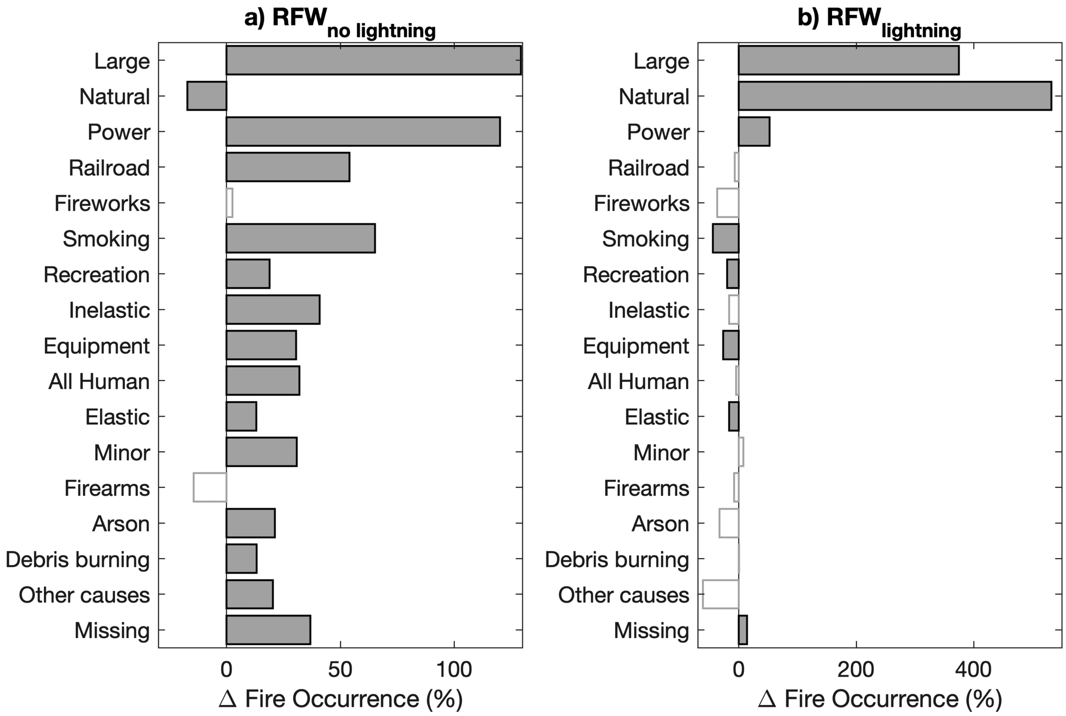

FIG. 4. Percentage difference between the average number of ignitions on (a) $\mathrm{RFW_{nolightning}}$ and (b) $\mathrm{RFW_{lightning}}$ relative to pseudocounterfactual days. Solid bars indicate statistically significant differences ($p < 0.05$, and 95% confidence interval did not include zero difference). Results are aggregated across all WFOs in the 11 western states.

Northwest, southwestern California, and Colorado, where more fires occurred on RFW days (Fig. 5c). By contrast, within the boundaries of most weather forecast offices, the number of fires ignited by inelastic human causes was significantly greater on RFW days than on pseudocounterfactual days (Fig. 5e). The number of natural fires was significantly greater on RFW days with lightning than on pseudocounterfactual days within most weather forecast offices outside of Arizona, Southern California, and southern Nevada (Fig. 5b). Within most weather forecast offices, the number of natural fires was significantly lower on RFW days without lightning than on pseudocounterfactual days, as would be expected (Fig. 5a).

Across the western United States, the conditional probability of an ignition becoming a large wildfire was considerably greater on both RFW days with lightning (7.6%) and RFW days without lightning (7.5%) than on all days of the year (3.9%). The conditional probability of a fire becoming large was significantly greater on RFW days without lightning than on pseudocounterfactual days across about half of weather forecast offices (Fig. 6a). Pooled across all weather forecast offices, the conditional probability of an ignition becoming a large fire was one-third higher on RFW days without lightning (7.6%) than on pseudocounterfactual days without lightning (5.6%). By contrast, for the vast majority of weather forecast offices, differences in the conditional probability of an ignition becoming large on RFW days with lightning and pseudocounterfactual days were not significant (both 7.5%; Fig. 6b). We did not directly compare the number of large fires on RFW days and pseudocounterfactual days.

4. Discussion and conclusions

Red flag warnings (RFWs) were issued on more than 10 days yr^{-1} across much of the interior western United States, with the greatest number across much of New Mexico and eastern Colorado. By contrast, few RFWs were issued in the maritime coastal zones of the Pacific Northwest and areas dominated by irrigated agriculture in California's San Joaquin Valley. The seasonality of RFWs generally overlaps with that of the core fire seasons across the western United States (Abatzoglou et al. 2018b; Westerling et al. 2003). However, in California, fires are largest from May through September (Williams et al. 2019), whereas most RFWs are issued from September through December, corresponding with the peak season for downslope wind-driven fires (Abatzoglou et al. 2023). This likely reflects that criteria for issuance of RFWs include the potential for wind-driven fires, which have different behavior than fuel-driven fires during summer.

That fires, particularly large fires, disproportionately ignite on RFW days is not surprising. Many high-profile fires in the western United States ignited concurrent with an RFW (Mass and Ovens 2021; Nauslar et al. 2018). Nineteen percent of lightning-caused fires occurred on RFW days. Lightning is a key ignition source, particularly in sparsely populated areas. RFWs in the northwestern United States were more strongly

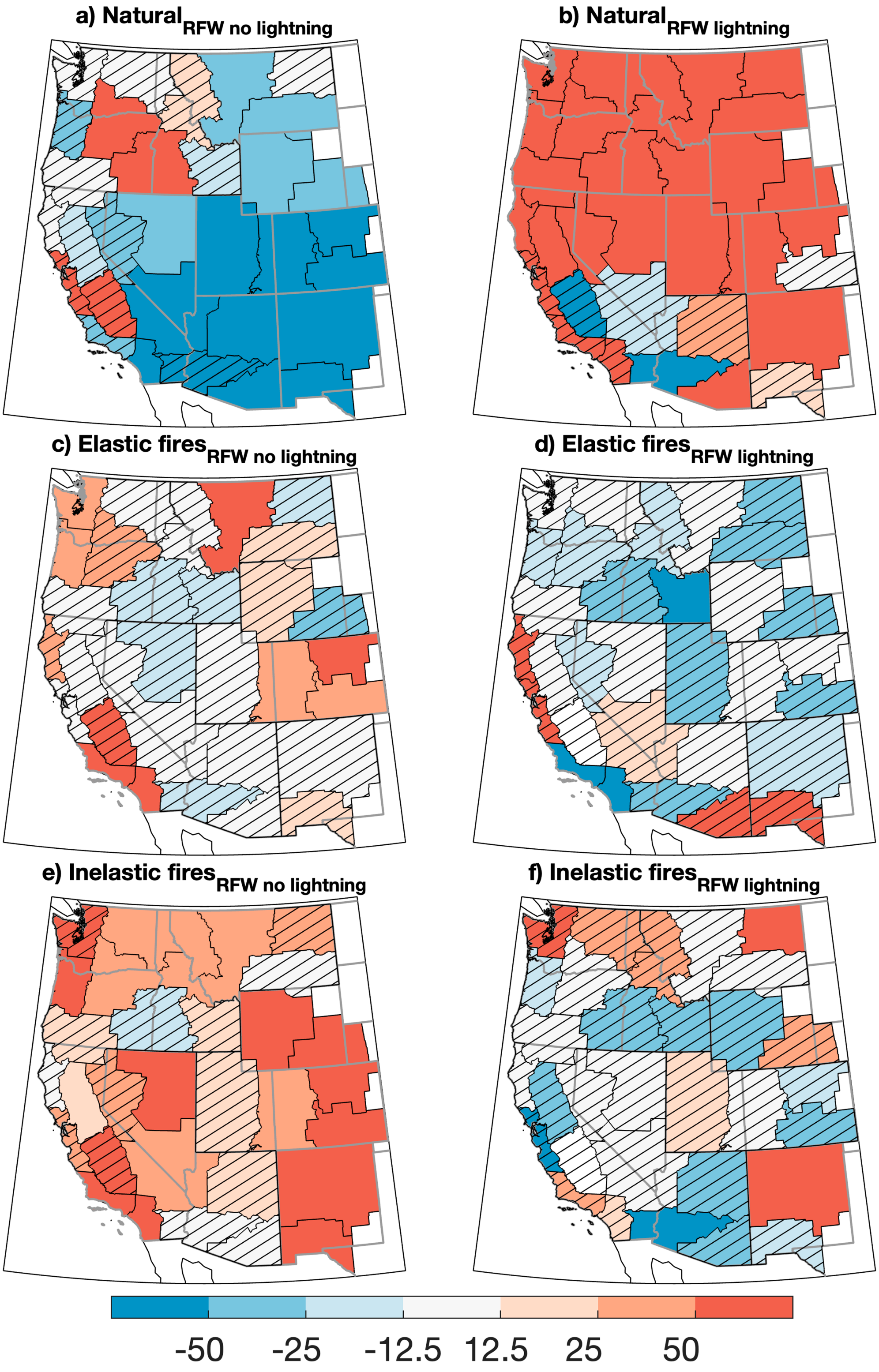

FIG. 5. Difference (%) in the number of wildfires per WFO ignited by (a),(b) natural causes (lightning); (c),(d) elastic human causes (debris burning, firearms, fireworks, and recreation); and (e),(f) inelastic human causes (arson, equipment, minor, power, railroad, and smoking) between days with RFWs and pseudocounterfactual days from 2006 to 2020. (a), (c), and (e) show differences on RFW days without lightning, whereas (b), (d), and (f) show differences on days with RFWs with lightning. Hatching denotes WFOs for which differences between days with RFWs and counterfactual days were not statistically significant ($p > 0.05$).

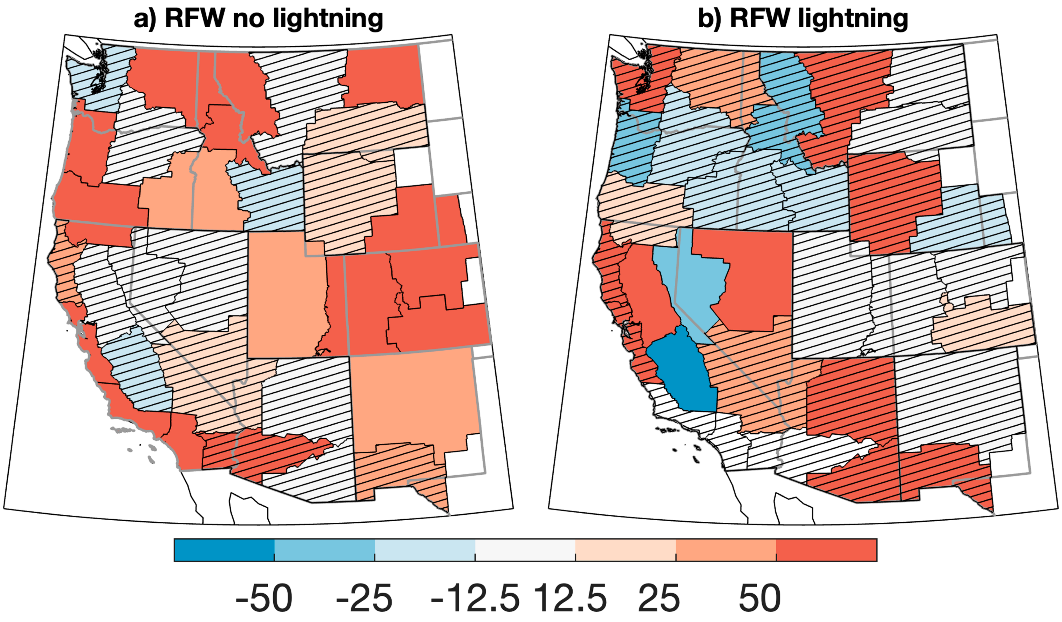

FIG. 6. Percentage difference in the likelihood of an ignition becoming a large (≥40 ha) fire between (a) $\mathrm{RFW}_{\mathrm{nolightning}}$ and (b) $\mathrm{RFW}_{\mathrm{lightning}}$ and pseudocounterfactual days at the level of WFO boundaries. WFOs shown in gray indicate where no large fires occurred on pseudocounterfactual days. Hatching denotes WFOs for which differences were not statistically significant ($p > 0.05$).

linked to large lightning-caused fires than to large human-caused fires, where large was defined as the 80th, 90th, or 95th percentile within the region (Clark et al. 2020). Yet 95% of RFWs occurred on days without lightning, suggesting that these warnings were issued on the basis of the potential for growth of ongoing fires or human-caused ignition of new fires with the potential to escape the initial attack and become large. Direct comparisons between our results and those of Clark et al. (2020) are not feasible given differences in methods and fire-size thresholds. Nevertheless, we suspect that the difference in results primarily reflects the number of lightning ignitions on RFW days (Fig. 5b) rather than the conditional probability that a lightning ignition becomes a large fire (Fig. 6b).

Although the number of human-caused fires was higher on RFW days than on pseudocounterfactual days, RFWs appeared to affect ignitions with elastic human causes to a greater extent than those with inelastic causes. On days with active RFWs, the probability of ignitions caused by short-term behavioral decisions was lower than that of ignitions associated with infrastructure or habitual behavior. For example, the number of fires caused by debris and open burning was only 10% higher on RFW days than on pseudocounterfactual days; across the west, 5% of fires caused by debris and open burning occurred on RFW days. Residents who burn debris or yard waste, sometimes to create defensible space, often do so irregularly and, during some seasons, must do so with a permit. Whether motivated by permit requirements or general safety concerns, these individuals may be attentive to weather forecasts (including RFWs) and fire restrictions to ensure safe burning and prevent property loss (Calkin et al. 2013; Thapa et al. 2023). By comparison, the number of fires caused by power infrastructure was more than twice as high on RFW days than on counterfactual days, with 13% of fires caused by power infrastructure occurring on RFW days. The relative increase in the number of fires ignited by elastic causes (+10%) was lower than the number ignited by inelastic causes (+36%), suggesting that RFWs discourage certain behaviors that lead to potential ignitions. Due to data limitations, we did not examine whether the efficacy of RFWs changed during the study period. However, cumulative impacts from past fire seasons may have increased awareness of fire potential and contributed to relative improvements in the efficacy of such warnings as an indirect fire prevention measure.

Several caveats to our work suggest areas for additional study. First, the dates on which fires are discovered are not always their ignition dates. This is particularly true for lightning-caused fires, especially in remote areas, that ignite during precipitation events and initially remain small but grow and are detected several days later (Kalashnikov et al. 2023). However, such cases represent a small percentage of fires (Schultz et al. 2019), and the dates of discovery and ignition of human-caused fires are more likely to be the same. Second, the criteria that each weather forecast office used to issue an RFW were not readily available, impeding our ability to identify weather conditions (e.g., wind) associated with each warning. Third, our pseudocounterfactuals do not capture the same fire weather conditions present during each RFW and are an incomplete means of assessing whether RFWs prevent fires and may underestimate the magnitude of their efficacy. For example, measures of ignition potential such as the ignition component of the U.S. National Fire Danger Rating System

(Cohen and Deeming 1985) combine the odds of a firebrand igniting dead vegetation (driven by temperature, humidity, and radiation) and the odds of that ignition becoming a discoverable fire (driven by wind and fuel moisture), both of which are likely higher on RFW days than on pseudocounterfactual days. Fourth, additional biophysical (e.g., vegetation) and social (e.g., primary language spoken, income) metrics may further aid in the understanding of the patterns shown herein. For example, future research might assess whether issuing RFWs in multiple languages affects the number of ignitions with elastic causes (O'Brien et al. 2018; Trujillo-Falcón et al. 2021) or whether the number of fires ignited by certain elastic causes is related to social and economic marginalization, such as debris and open burning when landfill or yard maintenance services are not readily available (Ballard et al. 2024). We suggest that future research explores the multiple ways in which fire weather warnings such as RFWs may not only prevent fires but also promote situational preparedness, including actions such as gathering evacuation supplies and becoming mentally ready to leave if necessary, and community readiness.

Although the National Weather Service is committed to RFWs as a tool for mitigating fire risks (defined as the integration of hazard and exposure), our results suggest that their effectiveness for fire prevention is limited. Warnings of other latent hazards, such as heatwaves, also have modest effects (Weinberger et al. 2018). As warning systems are not standardized nationally, agency-specific fire hazard systems may confuse the public (Jakober et al. 2023). However, our results may also reflect that RFWs were not explicitly designed for fire prevention, and communication and messaging of such warnings often fall to other federal and state agencies or media outlets. Weather warnings, including RFWs, may not reach everyone at risk if they are not distributed through the diverse channels that people use to access information (Vélez et al. 2017). Furthermore, studies on fire prevention show that while education and communication efforts are helpful, barriers to adoption and action persist (Hesseln 2018). Also, challenges in communication about proactive and reactive reduction of wildland fire risk between agencies and residents may carry over to RFWs (Remenick 2017). In some parts of the western United States, RFWs are in effect on an average of over 30 days yr^{-1}, potentially leading to fatigue and reducing public responsiveness to such warnings (Mackie 2014).

Our results highlight the relevance of improving the efficacy of RFWs. For example, the National Weather Service has rarely used the particularly dangerous situation (PDS) designation for fire weather despite the use of such language in forecast discussions. However, a recent effort aims to implement a new tier of RFWs for rare, extreme fire weather conditions across the western United States. Fires already are more likely to become large on days with RFWs. As climate change intensifies fire weather conditions over the coming decades, ignitions on RFW days could lead to even larger fires that affect more people. Given that human activity is a primary source of ignitions on RFW days, avoiding such ignitions could reduce some of the increased risk of wildfires across the West.

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Data availability statement. The data we analyzed are available through public repositories: 1) Catalog of red flag warnings from Iowa Environmental Mesonet: https://mesonet.agron.iastate.edu/, 2) wildland fire ignition data from the Fire Program Analysis fire-occurrence database provided by the U.S. Forest Service Research Data Archive: https://www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.6, 3) lightning strike data from the National Centers for Environmental Information Severe Weather Data Inventory: https://www.ncei.noaa.gov/products/lightning-products, and 4) surface meteorological data from gridMET: http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_MET_catalog.html.

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