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Wildfire, smoke, and outdoor recreation in the western United States

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ABSTRACT

Wildfire activity is increasing in the western United States at a time when outdoor recreation is growing in popularity. Because peak outdoor recreation and wildfire seasons overlap, fires can disrupt recreation and expose people to poor air quality. We link daily data on campground use at 1069 public campgrounds across the western United States over a ten-year period to daily satellite data on wildfire and smoke. We use this data set to (1) tabulate the number of campers affected by wildfire and smoke at campgrounds across the western US, and (2) provide estimates of how campground use responds to wildfire and smoke impacts, including the first causal estimates of the impacts of wildfire smoke on recreation behavior. We find that, on average, more than 120,000 campground visitor-days per year are close to an actively burning fire and nearly 400,000 are impacted by adverse smoke conditions. In some regions more than 10% of camper-days occur when air quality is poor due to wildfire smoke. Combining the results with monthly national park visitation data at the 30 parks in our sample, we estimate that fire and smoke affect 400,000 and 1 million visitor-days per year, respectively. Using fixed effects panel regressions at the campground level, we estimate declines in campground use in response to fire and smoke. The magnitude of the smoke effect is small, however, suggesting that smoke fails to deter most visitors to public lands. Back-of-the envelope calculations based on our findings and estimates from the literature suggest that most of the total welfare losses accruing to campers due to smoke occurs via health impacts from trips taken in spite of smoky conditions, rather than due to cancelled trips.

1. Introduction

Outdoor recreation on public lands in the United States has never been more popular. National parks saw 327.5 million visitors in 2019, and the six highest-visitation years on record were 2014–2019 (NPS, 2019). Visits to Bureau of Land Management (BLM) sites, such as national monuments and national conservation areas, rose by 20% over the past ten years (BLM, 2019). In the western United States, where more than half the land is owned by the federal government and many of the most famous national parks are located (including the Grand Canyon, Glacier, Yellowstone, and Yosemite), outdoor recreation is a significant economic driver. In Montana, for example, outdoor recreation accounts for 5% of state GDP, compared to 2.2% nationally (BEA, 2019).

As outdoor recreation has increased in popularity, wildfires in the American West have become more frequent and more severe (Abatzoglou and Williams, 2016; Westerling, 2016; Crockett and Westerling, 2018). Wildfires pose a problem for outdoor recreation for three reasons. First, they frequently burn on public lands used for recreation, in some cases impacting visitor experiences for years into the future (Englin et al., 2001; Hesseln et al., 2003; Hilger and Englin, 2009). In 2018, 63% of the acreage burned in wildfires in the western United States was on federal lands (Hoover and Hanson, 2019). Second, fire season coincides with outdoor recreation season. Approximately 48.5% of visits to national parks in 2018 occurred between June and September, which overlaps with peak wildfire season in many parts of the western US (NPS, 2019). Third, outdoor recreationists spend large amounts of time outside. Recent estimates indicate that up to half of $PM_{2.5}$ exposure in some parts of the western United States is attributable to wildfire smoke (Burke et al., 2021). Exposure to unhealthy air quality from wildfire smoke can reduce enjoyment of the recreation activity, lead to respiratory health problems, and offset the health benefits of physical activity (Korrick et al., 1998).

Much of the literature on wildfire and outdoor recreation has focused on the impacts that a fire-damaged landscape has on recreation in the years after a fire. Using a combination of recreation site visit data and responses to survey questions about visitation under hypothetical fire

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conditions, studies have examined how various fire characteristics, such as size, severity, and age, affect the frequency of trips and the value of outdoor recreation (Englin et al., 2001; Hesseln et al., 2003; Loomis et al., 2001; Hesseln et al., 2004; Starbuck et al., 2006; Boxall and Englin, 2008; Sánchez et al., 2016). These studies typically focus on relatively small geographic areas and a limited number of fires, or sometimes a single fire event. Two studies have used multiple years of national park visitation data to analyze how fire affected visitation in Yellowstone National Park (Duffield et al., 2013) and five national parks in Utah (Kim and Jakus, 2019). Some studies have used the effects of fire as a way to assess the value of forest characteristics, including forest age (Englin et al., 2006*)*.

The effect of wildfire smoke on recreation has received decidedly less attention. Two studies collected survey data to analyze how outdoor activity, including exercise and recreation, changed in response to a wildfire event (Richardson et al., 2012; Fowler et al., 2019), but these studies were focused in urban areas. We are aware of only one study focused on evaluating the impact of wildfire smoke on outdoor recreation away from home, a recent paper that used a case study and survey approach to evaluate changes to public lands users' recreation experiences and trip planning (White et al., 2020). A few studies have examined effects of air quality on recreation. For example, a 2018 study using monthly visitation data found that air pollution is about as severe in some national parks as in US urban areas, and that it negatively affects visitation (Keiser et al., 2018).In a study of the effect of smog alerts on outdoor recreation in southern California, Graff-Zivin and Neidell (2009) found that residents make short-run adjustments to shift outdoor activities from days with smog alerts to days with better air quality. However, the specific effects of wildfire smoke on outdoor recreation are largely unexplored, and several studies show that exposure to particulate matter (PM) from smoke has different effects on health outcomes and behavior than exposure to PM from typical urban sources (Kochi et al., 2010).

We combine daily observational data on outdoor recreation over a ten-year period across the western continental United States, daily satellite data on wildfire burn areas and smoke plumes, and ground-level air quality monitoring data. We assess the impact of wildfire and smoke on outdoor recreation across a large region and multiple fire events. Our recreation data are drawn from the Recreation.gov website, which is used to make reservations for a variety of activities at more than 3700 federally managed facilities across the United States. We focus on camping, one of the most popular nature-based recreation activities and the source of most reservations in the Recreation.gov system. Camping has relatively high smoke exposure, given the many hours campers spend outdoors. Our data include camping reservations and walk-in registrations at more than 1000 individual campgrounds in the western United States on each day of the year from 2008 through 2017 and information on reservation cancellations and early check-outs.

We address two main research questions. First, we ask how many people are directly affected by wildfires and wildfire smoke each year while camping on public lands in the western United States. Using these estimates, we calculate the share of total camper-days affected by wildfires and smoke and the spatial variation of the impacts across the region. The daily data from the Recreation.gov system allows us to calculate the first comprehensive estimates of fire and smoke impacts on outdoor recreationists. Compared to other data sources, which are often either survey-based and limited geographically or aggregate monthly or annual data, Recreation.gov provides daily counts of visitors at specific latitude-longitude locations (the locations of their reserved campgrounds). Not only does this give us a better understanding of the number of individuals in a recreation area at a given time, but once merged with daily data on fire and smoke, it allows us to estimate smoke and fire impacts at a much finer spatial resolution than in previous research. In addition to quantifying the number of campers affected, we combine our data with broader monthly visitation data for the national parks in our sample to estimate the total number of all visitors (not just overnight campers) at national parks affected by fire and smoke.

Second, we ask how fire and smoke alters campground use. Specifically, using panel fixed effects regression models, we analyze the following outcomes at the individual campground level: (i) campground occupancy rates, (ii) trip cancellation rates prior to arrival, and (iii) trip cancellation rates after arrival. The estimates from these models provide evidence on the extent to which people alter their recreation plans to avoid fire and smoke, and the first causal estimates thus far on the effects of wildfire smoke on outdoor recreation behavior. Our daily campground use data are particularly valuable for estimating impacts of wildfire smoke on visitation since wildfire smoke may be transient and short-lived.

Our analysis reveals that 124,000 campground visitor-days per year, on average, were within 20 km of an active wildfire over our ten-year sample period and nearly 400,000 campground visitor-days per year were affected by air pollution from wildfire smoke. Seventy percent of the campground visitor-days affected by fire and 42% affected by adverse smoke conditions were in California, highlighting both the prevalence of wildfire and popularity of outdoor recreation on public lands in the state. The northern states of Montana, Idaho, Washington, and Oregon accounted for only 16% of the campground visitor-days affected by fire but 38% of the visitor-days affected by smoke, underscoring the tendency of smoke to travel long distances with prevailing winds from south to northeast. Moreover, because of the shorter outdoor recreation season in the north, these four states had the greatest share of campground visitor-days affected by smoke, 7% over the ten-year period. A total of 392,000 national park visitor-days per year were near a wildfire, and 1 million park visitor-days per year were affected by air pollution from wildfire smoke.

Finally, our regression results show statistically significant impacts on campground occupancy rates and cancellation rates from fire and smoke. When a fire is within 20 km of a campground, the occupancy rate drops 6.4 percentage points, on average, and cancellation rates before arrival more than double. The magnitudes of the smoke impacts are comparatively small, however. The occupancy rate falls by only 1.3 percentage points under adverse smoke conditions. We attribute this small effect, in part, to the challenge of finding an open campsite at many national parks in the peak summer months (Walls et al., 2018). Cancelling a trip because of smoky conditions may mean foregoing a visit for the entire season, which many travelers may be unwilling to do. Indeed, we estimate separate regressions by campground popularity quartiles and find that smoke has the smallest effect on occupancy rates in the most popular campgrounds. In a back-of-the envelope welfare calculation, combining our results with valuation estimates in the literature, we find that wildfire smoke causes welfare losses from smoke-related illnesses and avoided camping trips of approximately $4.8 million per year. These losses are an underestimate of the full welfare loss, as they do not include the disutility of camping during smoky conditions. Nonetheless, they provide some sense of the welfare losses to outdoor recreationists from wildfire smoke—losses that are likely to rise as wildfire activity continues to escalate in the western United States.

2. Data and methods

2.1. Recreation data

We assembled a panel dataset comprising daily campsite reservations, proximity to active wildfires, and air-pollution-related smoke conditions at federally managed campgrounds. We source the data from Recreation.gov. Though not all federally managed campgrounds are reservable, and some sites are managed through alternative systems, Recreation.gov is the primary online system through which visitors can make and cancel reservations at federal campgrounds. We obtained historical data for 2008–2017 from the website managers. The complete database includes 90 million transactions by 7 million unique users of federal outdoor recreation facilities for each day of the year between

2008 and 2017. We focus on campground facilities in the 11 western continental US states, reducing the dataset to approximately 25 million transactions by 3.1 million unique users at 1069 campgrounds managed by the US Forest Service, BLM, the US Army Corps of Engineers, National Park Service (NPS), and Bureau of Reclamation. Campgrounds in our dataset belong to 269 distinct "recreation areas," which include national parks, lakes, or reservoirs managed by the Army Corps of Engineers, ranger districts in national forests, and resource areas or districts managed by BLM.

Our dataset includes all transactions online, by phone, and on-site (such as walk-in reservations or early check-outs). For the western campgrounds in our analysis, 81% of transactions were made online, 10% over the phone, and 9% on-site. The dataset includes the date of each transaction, the scheduled arrival and departure dates, payments, dates of cancellation, group size, zip code of origin, and campground information. For most campgrounds, we do not observe whether the individual checked in to the campground on the scheduled date, so we cannot identify "no-shows" at all locations. However, campers have a financial incentive to cancel when plans change, mitigating this concern. They usually receive a full refund less a $10 service fee if they cancel more than one day prior to the scheduled arrival date and a full refund less a $10 service fee plus the cost of one night's stay when they cancel within one day of the scheduled arrival date. We aggregate reservation records from the individual campsites to the campground level to construct a daily panel of use measures for each campground in our dataset. Our measures of interest are the number of occupants, occupancy rate (i.e., the share of sites in use), and pre- and post-arrival cancellation rates (the number of reservations cancelled prior to arrival and during the stay, respectively, as a share of all reservations). Appendix A provides more information about the construction of the dataset from the raw Recreation.gov database.

For every campground we determine the number of daily occupants based on the number of uncancelled reservations. We measure the occupancy rate on date t as the proportion of campground sites that are reserved (and for which reservations have not been cancelled) on date t. Formally, the occupancy rate variable is ($occupied\ campsites_{it}$)/($total\ number\ of\ campsites_{it}$). The occupancy rate provides a measure of overall site use, which we expect will decline during nearby wildfire activity or periods of heavy smoke, due to both decreases in new reservations and increases in cancelled reservations. Appendix A describes how we calculate the total number of campsites (the denominator in the occupancy rate variable) for each campground on each day.

We also consider two measures of cancellations. The pre-arrival cancellation rate is the number of cancelled reservations as a share of total reservations for arrival date t. We consider only the cancellations that occurred within one week of arrival, because these trips are most likely to be influenced by current and anticipated fire and smoke conditions.

Visitors may also decide to end their visit early in response to fire or smoke. Therefore, for each campground, we also measure the post-arrival cancellation rate as the number of cancellations made on date t for visits that began prior to date t and had a scheduled departure date after day t, calculated as a share of the number of occupants at the campground on day t.

In a supplementary analysis, we estimate the total number of national park visitors (campers and noncampers) exposed to fire and smoke. For this analysis, we use data from NPS Visitor Use Statistics, which provide monthly visitation data for individual national parks (NPS, 2019). We combine these data with our estimates of calculated exposure of campground users to obtain an estimate of total numbers of national park visitors affected by fire and smoke.

2.2. Active fire and smoke data

Locations of active wildfires come from MODIS fire detection data (Giglio et al., 2016). MODIS is an instrument aboard NASA's Terra and Aqua satellites capable of detecting fire activity. MODIS fire detection data provide centroids of 1 km observations with a temporal resolution of 1–2 days for all observed fire activity, including agricultural burning and prescribed fires. We restrict fire detections to those associated with wildfires by selecting those near in space (within 1 km) to and occurring during the same time as wildfires in the USGS Monitoring Trends in Burn Severity (MTBS) dataset, which maps perimeters of wildfires larger than 1000 acres in the western United States (Eidenshink et al., 2007). An advantage to using this modified MODIS dataset, rather than simply the final fire perimeters from MTBS, is that MODIS data more reliably identify the period during which fires are actively burning. We measured the distance between each campground and the nearest active wildfire for each date in the study period and used that distance to identify campgrounds that were within 20 km of an actively burning fire on each date. In Appendix B, we show results for alternative distances.

Days with adverse smoke conditions are based on data from the NOAA HMS and the US Environmental Protection Agency (EPA). Since 2005, NOAA analysts have used imagery from GOES satellites to map smoke plume boundaries. Usually twice a day—once in the morning and once in the evening—analysts use 2–4 h satellite imagery animations to trace polygons delineating the boundary of each smoke plume they observe. They identify each plume as low, medium, or heavy smoke. The NOAA HMS smoke product has been used recently in studies of smoke's contribution to air pollution and air pollution's effect on crime (Preisler et al., 2015; Burkhardt et al., 2019). A disadvantage of the NOAA HMS smoke data is that because plumes are identified based on aerial imagery, and smoke may be high in the air column, they do not necessarily identify locations with poor on-the-ground air quality. We combine the smoke data with data provided by Burkhardt et al. (2019), who interpolate EPA daily surface-level $PM_{2.5}$ monitoring data to a 15 km grid using kriging, a geostatistical spatial interpolation method that has been shown to be effective for air quality data over large areas (e.g., Jerrett et al., 2005). The data and interpolation method are described in detail in Burkhardt et al. (2019). Following their approach, we calculate seasonal means and standard deviations of air quality on days that each cell is not covered by a smoke plume. We then identify air-quality-impacted smoke days as days on which a campground is covered by a smoke plume and $PM_{2.5}$ is at least 1.64 standard deviations above the within-cell seasonal mean for nonsmoky days, which represents the 95th percentile of a normal distribution. This method eliminates many of the areas covered by smoke plumes because they fall below the 95th percentile for $PM_{2.5}$. In Appendix B, we show results for an alternative, less conservative, assumption using only the smoke plume data without the adjustment from the ground-level monitors.

2.3. Quantification of total wildfire and smoke impacts on outdoor recreation

The first part of our analysis involves a spatial merge of the campgrounds in our dataset with the wildfire data and combined smoke plume-$PM_{2.5}$ monitor data to calculate the total number of campground-days near wildfires and affected by adverse smoke conditions over the 2008–2017 sample period. Using the total number of days the campground is open (as described in Appendix A), we then calculate the share of campground-days affected by fire and smoke in each year.

Using the reservation data from Recreation.gov, we tally the sum of campers at each campground on each day in our sample. An individual camper that visits a park for one day is tallied as a single camper-day. We merge the daily camper-days panel with the wildfire, smoke, and $PM_{2.5}$ data at the campground level and estimate the total number, and share, of camper-days affected by fire and smoke over the ten-year sample period.

Finally, we estimate the total number of national park visitor-days affected by fire and smoke by multiplying monthly visitor-days from the NPS Visitor Use Statistics database for each of the 30 national parks in our sample by the ratio of monthly camper-days affected to total

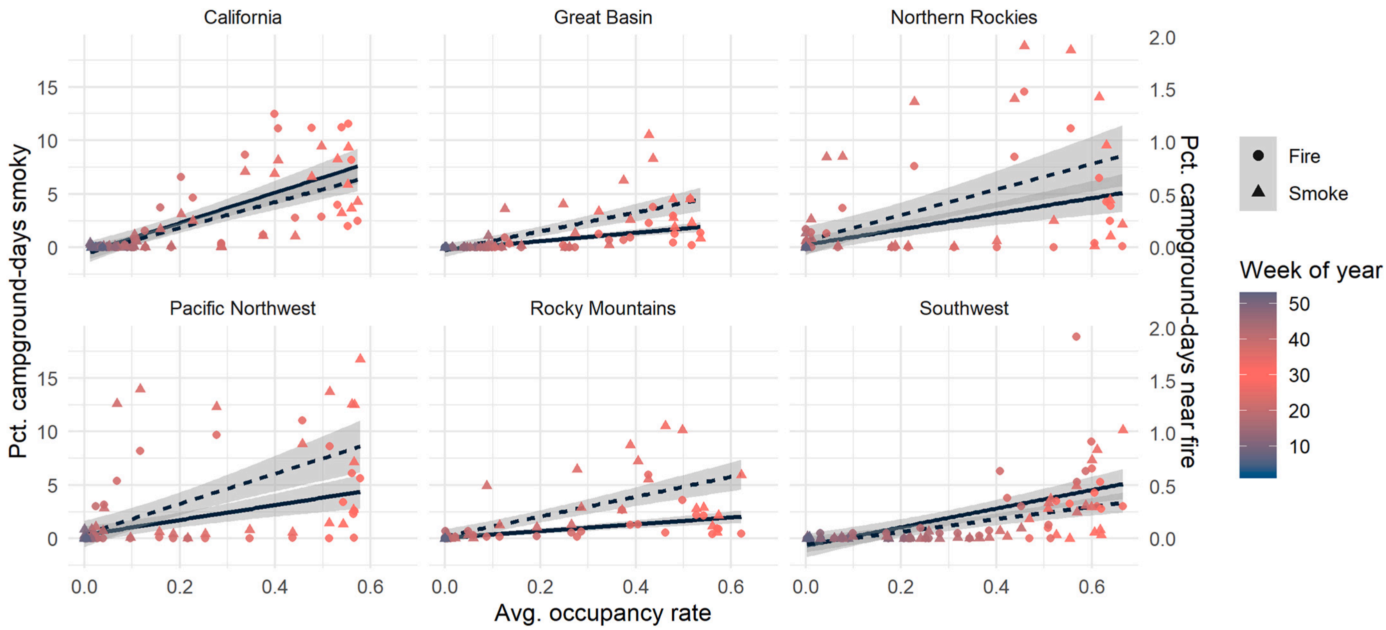

Fig. 1. Average overall campground occupancy and percentage of days with fire (circles) and smoke (triangles) within each region and week-of-year, 2008–2017. Solid and dotted lines show fitted values for fire and smoke, respectively, with shaded 95% confidence intervals. The six regions are defined in the text.

monthly camper-days at each park.

2.4. Analysis of behavioral responses to fire and smoke

We estimate the effects of wildfire and wildfire smoke on camping behavior at campground i on date t using the following regression specification:

$$y_{it} = \beta^f fire_{it} + \beta^s smoke_{it} + \gamma precip_{it} + \varphi temp_{it} + \psi_i + \delta_t + \lambda_{k(i),t} + \varepsilon_{it} \quad (1)$$

where y_{it} = {occupancy rate, pre-arrival cancellation rate, post-arrival cancellation rate} at campground i on date t; $fire_{it}$ is an indicator equal to 1 if a fire is within 20 km of campground i on date t; $smoke_{it}$ is an indicator equal to 1 if campground i is affected by adverse smoke conditions on date t; $precip_{it}$ is the amount of rainfall, in millimeters, at the campground on date t; $temp_{it}$ is the normalized difference between the campground's temperature on date t and its ten-year average on that week of year, where the normalization is based on the standard deviation of temperatures for that week; ψ_i is a set of campground fixed effects; δ_t includes week-of-year and day-of-week fixed effects and indicators for federal holidays; and $\lambda_{k(i),t}$ includes recreation area by month-of-year and recreation area by year fixed effects. The fixed effects control for seasonal factors and unobserved campground and recreation area characteristics that drive occupancy rates and cancellations. The precipitation and temperature variables control for weather effects that might affect camping decisions and outcomes. Thus, our model isolates the impacts of fire and smoke by controlling for a variety of unobserved factors that could be correlated with both fire and smoke and campground use. Regressions are weighted by the number of campsites at campground i on date t to account for heteroskedasticity.[1] Standard errors are clustered at the recreation area level to allow for errors to be correlated across campgrounds in the same area.

In Appendix B, we test distance bandwidths of 10 km and 30 km for the fire variable and relax our measure of adverse smoke conditions by using the smoke plumes data without the ground-level $PM_{2.5}$ readings adjustment.

3. Results

3.1. Campgrounds and campground visitor-days affected by wildfire and smoke

Consistent with our initial expectations and the findings of previous literature, we find that there is greater recreational activity during times of year with more wildfires and smoke events. Participation in camping and other outdoor recreation activities on public lands is highly seasonal. Good weather, long hours of daylight, school holidays, and other factors lead most people to national parks and other recreation areas during summer months, when wildfires are most common. Fig. 1 plots average overall campground occupancy rates in each region and week of the year against the frequency of campground-days with smoke (left y-axis) or a wildfire nearby (right y-axis) for six subregions of the western United States. Each triangle (fire) and circle (smoke) is colored by week—redder colors are closer to the middle of the summer, and bluer colors correspond to winter.[2] In each region,[3] campgrounds are more likely to be impacted by fire and smoke during high-use times of year, especially summer. Campgrounds in our sample were near active burning fires (within 20 km) an average of 1.5 days per year, corresponding to 1.7% of the days those campgrounds were open (Table 1, panel I, columns 1 and 2). The frequency with which campgrounds experienced nearby fires varied across western subregions. In Southwest states (Arizona and New Mexico) and California, campgrounds experienced nearby fires more than two days per year on average, and the Rocky Mountains (Colorado and Wyoming) and Great Basin (Nevada and Utah) campgrounds had fires nearby an average of only 0.5 days per year. The result for California is relatively high because wildfires were

[1] Breusch-Pagan statistics from non-weighted and non-clustered versions of regressions in Table 4 are 3091, 3325, and 3463, respectively, leading us to reject the null hypothesis that errors are homoskedastic.

[2] Each panel contains 52 circular markers and 52 triangular markers, corresponding to the 52 weeks in the year we average over, 2008–2017, to construct the plot.

[3] Regions are California, Great Basin (Nevada and Utah), Northern Rockies (Idaho and Montana), Pacific Northwest (Oregon and Washington), Rocky Mountains (Colorado and Wyoming), and Southwest (Arizona and New Mexico).

Table 1
Annual campground- and camper-days near wildfires and with adverse smoke conditions, by region.

	Campground-days		Camper-days	
	Avg. annual days per campground	Percent of total available campground-days	Avg. annual camper-days (thousands)	Percent of total camper-days
I. Fire				
California	2.5	2.0	86	2.1
Great Basin	0.5	0.6	3	0.3
Northern Rockies	1.5	1.9	7	1.0
Pacific Northwest	1.5	2.2	13	0.9
Rocky Mountains	0.5	0.6	2	0.2
Southwest	2.1	2.0	14	1.8
Total	1.5	1.7	124	1.4
II. Smoke				
California	6	5	160	4
Great Basin	4	5	23	3
Northern Rockies	9	11	49	7
Pacific Northwest	9	12	95	7
Rocky Mountains	6	7	41	4
Southwest	4	4	15	2
Total	7	7	383	4

Notes: Campground-days are the number of days campgrounds in each region were within 20 km of an active fire (Panel I) or had adverse smoke conditions (panel II). Camper-days multiply the number of days campgrounds in each region were affected by the number of campers at each campground on affected days. Each campground's total available campground-days are calculated as the number of days each year the campground had at least one occupant.

common in the state. Fires were less frequent in the Southwest, but those that did occur were often close to federally managed campgrounds, especially the Grand Canyon. Within a larger distance of 30 km to the nearest fire, more campgrounds were affected: an average of 2.8 days per year, or 3.0% of the days campgrounds were open during the period (Appendix B).

On average, 124,000 camper-days per year were within 20 km of an active wildfire, and 86,000 of these—nearly 70%—were in California (Table 1, panel I, columns 3 and 4). As a share of total camper-days, the number near an active fire ranged from an average of 0.2% in the Rocky Mountains to 2.1% in California; the overall average was 1.4%. If we relax the distance bandwidth to 30 km within an active wildfire, the number of affected camper-days rises to 218,000, and the percent of affected days rises to 2.5 (Appendix B).

In contrast to fire, smoke affects campgrounds and campers more often. On average, across the western states, campgrounds experienced adverse smoke conditions seven days per year, representing 7% of the days that campgrounds were open (Table 1, panel II, columns 1 and 2). Campgrounds in the Northern Rockies (Idaho and Montana) and Pacific Northwest states (Oregon and Washington) were especially affected, with 10 and 12% of campground-days, respectively, experiencing adverse smoke conditions. These subregions have actively burning wildfires less frequently than other regions, but prevailing wind patterns bringing smoke from fires in the south mean that they are disproportionately affected by smoke. Not only was the average number of smoky days higher than in other subregions, but the percent of available campground-days affected by smoke was much higher due to the shorter camping season in those subregions, particularly in the Northern Rockies.

Nearly 400,000 camper-days per year, on average, were under adverse smoke conditions during our sample period, with 160,000 in California (Table 1, panel II, columns 3 and 4). However, that number accounts for only 4% of all camper-days in California, much lower than the Pacific Northwest and Northern Rockies subregions. This difference likely owes to the comparatively longer camping season in California. By contrast, in the Northern Rockies, 7% of camper-days were under adverse smoke conditions. On average, across the western continental United States, 4% of camper-days had air quality impaired by wildfire smoke. These findings suggest that a nontrivial portion of the camping season is impacted by poor air quality due to smoke in many parts of the western United States.

Impacts show substantial regional heterogeneity. Fig. 2 combines the fire and smoke information in a map of the western United States. The gray base map shows the average number of annual days with adverse smoke conditions on a 15 km by 15 km grid. Smoke is most frequent in northern California and southern Oregon and along the Idaho-Montana border. Markers represent the location of campgrounds, with colors denoting the total number of campground-days with a nearby wildfire (within 20 km) over the study period. The map shows that California has a higher number of fire-affected campground-days than most other states. Colorado, for example, has many campgrounds but few campground-days near a fire, and Eastern Oregon has many days with smoky conditions but few campgrounds.

Although wildfire activity has increased in the western United States over the past several decades (Westerling, 2016), we observed no clear trend in the number of campground-days near wildfires over 2008–2017 (see Fig. B1 in Appendix B). The 10-year study period is likely too short to observe longer term trends in campground impacts, especially given the substantial year-to-year variation in fire events.

3.2. National park visitor-days affected by wildfire and smoke

Campers are only a subset of all visitors at many federal recreation sites, particularly at national parks. Although we do not have daily data on all visitors, we can approximate the full impact of fire and smoke at national parks by combining our estimated fire- and smoke-affected camper-days with monthly total visitation data collected by the NPS. We find that, on average, 392,000 visitor-days per year at the national parks in our sample were close to active wildfires; Yosemite accounts for over half of this number (Table 2). Approximately 1 million visitor-days per year occurred during adverse smoke conditions, and these impacts were spread out across a larger number of parks. Once again, this highlights the wide-ranging effects of smoke across the region. Total visitor-days affected by fire and smoke exceed the numbers of camper-days at national parks by factors of 6 and 12, respectively.

3.3. Changes in recreation site use due to wildfire and smoke

Our results suggest a substantial number of people are affected every year by fire and smoke while recreating on public lands. In this section, we analyze the extent to which fire and smoke lead to averting behavior that affects campground use outcomes.

Table 3 displays summary statistics for the dependent variables of interest for estimation of eq. (3)—campground occupancy rates and pre- and post-arrival cancellation rates (as defined above). Before controlling for other factors, Table 3 shows evidence of changes in recreation site

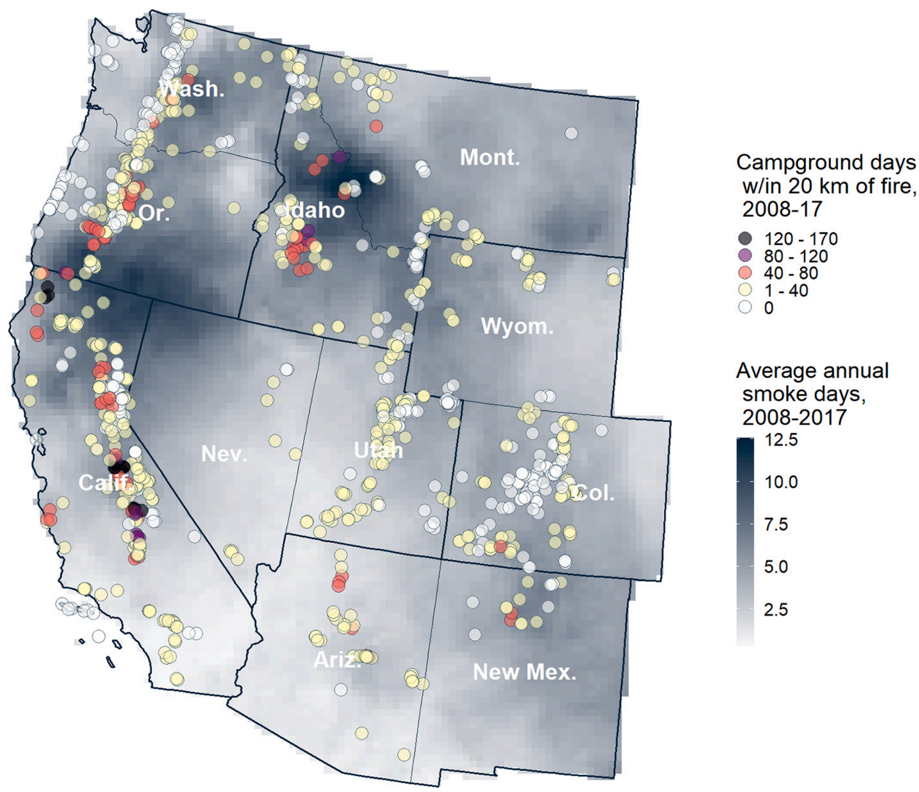

Fig. 2. Geographic distribution of smoke and fire impacts on campgrounds.

Table 2
Annual camper-days and annual estimated total visitor-days near fire and with adverse smoke conditions at selected national parks.

	Fire		Smoke	
	Camper-days per year (thousands)	Estimated total visitor-days per year (thousands)	Camper-days per year (thousands)	Estimated total visitor-days per year (thousands)
Yosemite National Park	47	206	40	175
Glacier National Park	2	51	7	159
Rocky Mountain National Park	0.009	0.8	7	110
Mount Rainier National Park	0	0	6	61
Grand Canyon National Park	9	91	4	43
Total (all parks in sample)	61	392	83	1000

Notes: Camper-days are the number of days campgrounds in each region were within 20 km of an active fire or with adverse smoke conditions, multiplied by the number of campers at each campground on affected days. Estimated total visitor-days with fire and smoke are calculated by multiplying total smoke and fire camper-days per month at each NPS site by the ratio of total visitors to campers at each site in that month.

Table 3
Summary statistics for campground recreational activity.

	Baseline Mean	Fire		Smoke	
		Mean	t-stat	Mean	t-stat
Occupancy rate	0.306	0.348	1.380	0.365	8.470
Pre-arrival cancellation rate	0.073	0.211	12.740	0.106	8.420
Post-arrival cancellation rate	0.002	0.021	7.400	0.004	4.110
No. of obs.	1,281,992	12,839		59,264	

Notes: The t-stat reported is from a test of the difference in means relative to the baseline (no smoke or fire), clustering at the recreation area level. The smoke variable indicates whether a campground had adverse smoke conditions; the fire variable is for active fires within 20 km of a campground. The observations are restricted to May through September.

use in response to fire and smoke. Column 1 reports means for a baseline scenario with no smoke or fire. Column 2 shows how mean occupancy and cancellation rates change when a fire is burning within 20 km. Column 4 reports mean values for dates with adverse air quality due to wildfire smoke. As expected, cancellation rates increase with fire or smoke. In contrast, occupancy rates are higher, on average, on dates with fire or smoke. This result may be because fire and smoke tend to occur during times of year that are popular for camping (Fig. 1). This highlights the need for a regression analysis that controls for these temporal effects.

Table 4 shows the results of estimating the model in eq. (3). We find statistically significant evidence that campground use decreases and

Table 4
Estimated effects of wildfire and smoke on campground use.

	Occupancy rate	Pre-arrival cancellation rate	Post-arrival cancellation rate
Fire	−0.064**	0.087**	0.013**
	[0.011]	[0.012]	[0.0019]
Smoke	−0.013**	0.023**	0.0014**
	[0.0022]	[0.0023]	[0.00037]
Mean of dep. var.	0.31	0.076	0.0024
No. of obs.	1,349,460	688,653	842,240
R^2	0.72	0.047	0.13

Notes: All columns include campground, recreation area by month-of-year, recreation area by year, week-of-year, and day-of-week fixed effects, as well as indicators for holidays and days before holidays. In addition, regressions control for the upcoming week's total precipitation. Campground observations are weighted by the number of campsites, and standard errors, shown in brackets, are clustered by recreation area. The observations are restricted to May through September.
** $p < 0.01$.

campground cancellations increase on smoky days and days when wildfires burn within 20 km. On days with nearby wildfires, the campground occupancy rate declines, on average, by 6.4 percentage points. With an average of 30.6% of campsites occupied in the baseline (Table 3), this indicates a drop to 24.6% when a fire is nearby. The pre-arrival cancellation rate increases by 8.7 percentage points with a fire nearby, more than double the baseline average cancellation rate of 7.3%. The post-arrival cancellation (or early departure) rate increases by 1.3 percentage points, an order of magnitude greater than the baseline average post-arrival cancellation rate, which is only 0.2%. Using a relaxed bandwidth of 30 km for the nearest fire, we still observe statistically significant effects: a campground occupancy rate that is 4.2 percentage points lower and increases in pre-arrival and mid-stay cancellation rates of 6.1 and 0.8 percentage points, respectively (Appendix B).

Our estimates for the effect of fire on recreation do not distinguish among several channels through which fires affect campground use. During fire events, campgrounds may close, causing reservations to be cancelled by the managing agency. Fires can also result in road closures, and even if roads remain open, campers may cancel if they are worried that further fire spread might disrupt their plans. We interpret our estimates of the effect of fire on campground use as inclusive of each of these channels.

The estimated effects of smoke on camping decisions are more modest (Table 4). On days with adverse smoke conditions, occupancy rates decline by only 1.3 percentage point (from 30.6% of campsites occupied to 29.3% for the average campground). Pre-arrival cancellation rates rise by approximately 2.3 percentage points (a 32% increase from the baseline average cancellation rate of 7.3), and post-arrival cancellation rates rise by one-tenth of a percentage point (nearly a 50% increase from the baseline rate). When using only smoke plumes to identify smoky days, estimated effects of smoke on occupancy and cancellation are more modest but remain statistically significant in most cases; high PM2.5 levels alone do not appear to decrease campground use (Appendix B).

Campgrounds and roads do not typically close due to smoke; therefore, we interpret changes in campground use as indicative of avoidance behavior on the part of campers. This behavior may be driven by concern over health impacts of exposure to smoke or by decreased amenity values due to diminished views. Regardless of motivation, we find that the magnitude of the resulting changes in total campground use is, on average, relatively small.

The detail provided in our daily damping data allowed us to further investigate differential avoidance behavior responses based on specific recreation areas. We posit that visitors could be more willing to camp during adverse conditions at a popular location like Glacier National Park relative to a smaller local campground. Limited visitation seasons at northern parks like Glacier, as well as competitive reservations at popular parks like Yosemite, could lead campers to brave the smoky conditions rather than forego a trip altogether. To test for heterogeneous

Table 5
Heterogeneity in responses to wildfire and smoke by popularity of campground.

	Occupancy rate	Pre-arrival cancellation rate	Post-arrival cancellation rate
Fire	−0.029*	0.112**	0.014**
	[0.011]	[0.024]	[0.004]
Smoke	−0.030**	0.022**	0.0005
	[0.004]	[0.004]	[0.001]
Fire × first quartile (most popular)	−0.044*	−0.048	−0.005
	[0.022]	[0.026]	[0.005]
Smoke × first quartile	0.027**	0.002	0.002*
	[0.007]	[0.005]	[0.002]
Fire × second quartile	−0.047*	0.010	0.010
	[0.021]	[0.031]	[0.007]
Smoke × second quartile	0.031**	−0.001	0.001
	[0.007]	[0.005]	[0.001]
Fire × third quartile	−0.047	0.016	0.007
	[0.025]	[0.031]	[0.005]
Smoke × third quartile	0.014*	−0.001	0.0003
	[0.006]	[0.004]	[0.001]
Mean of dep. Var.	0.31	0.076	0.0024
No. of obs.	1,349,460	688,653	842,240
R^2	0.72	0.048	0.13

Notes: All columns include campground, recreation area by month-of-year, recreation area by year, week-of-year, and day-of-week fixed effects, as well as indicators for holidays and days before holidays. In addition, regressions control for the upcoming week's total precipitation. Campground observations are weighted by the number of campsites, and standard errors, shown in brackets, are clustered by recreation area. The observations are restricted to May through September. Quartiles based on campground popularity as measured by mean occupancy rates over the sample period on days when campground is open.
** $p < 0.01$.
* $p < 0.05$.

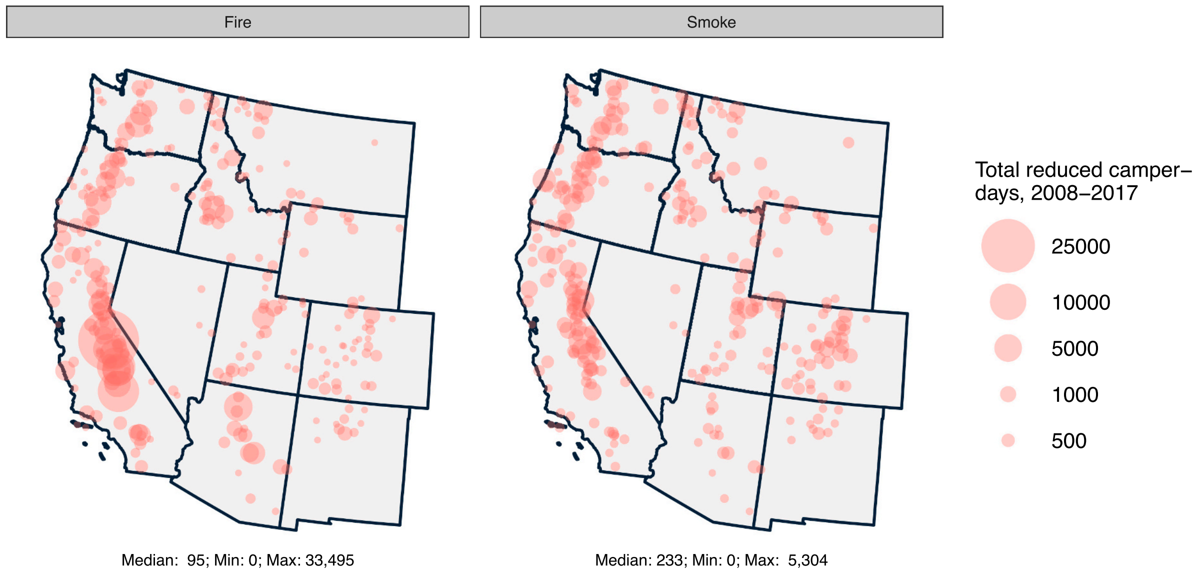

Fig. 3. Geographic distribution of recreational responses to smoke and fire.

responses, we ran a version of the regression that allows responses to fire and smoke to vary according to campground popularity. To determine popularity, we measured campgrounds' historical average occupancy rates and segmented the results into quartiles (Table 5). In line with our hypothesis, the occupancy rate was less responsive to smoke at the most popular campgrounds (the top occupancy quartile) than at less popular ones. We found no statistically significant differences in cancellation rates in response to smoke by site popularity, however.

Responsiveness to fire was greater at more popular sites. Fig. 3 uses our estimated regression results from Table 4 to map total declines in the number of camper-days due to fire and smoke over the course of the study period. We calculate declines in the number of campground-days due to fire (smoke) by multiplying the estimated fire (smoke) coefficient in the occupancy rate regression by the product of the average number of occupied sites at each campground on days without fire (smoke), the average number of campers per campsite at each campground, and the average number of days per year with fire (smoke) at each campground. We aggregate these campground figures to the recreation area level, which are the numbers shown on the map. Because fires tend to occur during times of year with greater occupancy (Fig. 1), we expect that these estimates understate total reductions in campground use due to fire and smoke.

The figure highlights several key findings. First, although fires occur infrequently at many locations, our regression results suggest that the marginal effects of fire on recreation behavior are relatively large. As a result, fires have large effects compared to smoke. This shows up as large circles on the fire maps, which are mainly in California—Yosemite in particular.

Second, although fire has much larger effects in some locations than others, the magnitude of the smoke effects is more consistent across locations. Fire caused much greater decreases in visitation than smoke at the most impacted campgrounds, but the median campground experienced 259 fewer camper-days per year on average due to smoke and only 95 fewer camper-days per year on average due to nearby fires. In subregions with comparatively few fires—namely, the Pacific Northwest and the Northern Rockies—smoke is still prevalent and has a similar impact on recreation behavior as in other locations.

Third, the consequences of fire and smoke for changes in recreation site use over the 10-year period are low to moderate in most places, but we see large impacts in some regions and years. In Yosemite, the recreation area most impacted by fire, nearly 3400 camper-days each year were lost due to fires. These impacts were not spread evenly across years. In 2012, the year of the Cascade fire, which struck Yosemite and surrounding areas in June and July, we estimate more than 8500 fewer camper-days due to nearby fire. Smoke also had its greatest effects in Yosemite: campers spent 590 fewer days per year there, on average, as a result of adverse smoke conditions.

We can combine our estimates of the reductions in camper-days from fire and smoke with consumer surplus values for outdoor recreation estimated in the literature to obtain a back-of-the-envelope estimate of the total annual consumer surplus loss to campers who forego their trips because of fire or smoke. Rosenberger et al. (2017) provide a review and summary of estimates of the value of fourteen outdoor recreation activities, including camping, on US Forest Service lands by region. Kaval and Loomis (2003) provide similar estimates for national parks, also by region. We combine the mean values from these two studies, which are per activity day per person, with our predicted declines in camper-days, and inflate to 2020 dollars. The consumer surplus loss from fire and smoke across the 11 western states in our study averages $1.3 million and $662,000 per year, respectively. Seventy-five percent of the consumer surplus loss from fire and 41% of the loss from smoke occurs in California.

In addition to losses from recreationists who forfeit their trips, there are also losses experienced by recreationists who continue with their plans but experience health effects or visual disamenities from smoke. Richardson et al. (2012), using survey data from households in the Los Angeles area after a major fire, estimate an average cost of smoke-related illness (costs of medications, doctor visits, and missed work-days) per exposed person per day of $9.50. Inflating to 2020 dollars and multiplying by the average number of camper-days affected by adverse smoke conditions per year (383,000, from Table 1), we estimate illness costs of $4.1 million per year. This may be an underestimate since our adverse smoke conditions measure is conservative and omits some days with low density smoke, which nevertheless may impact health. Using the average number of camper-days per year that intersect a smoke plume (1588,000, from Table B1) in place of the average number of camper-days with adverse smoke conditions, we estimate illness costs of approximately $15.1 million per year. Adding these costs to the losses from avoided trips gives a total losses of $4.8–$15.8 million per year from wildfire smoke. This calculation is back-of-the-envelope and underestimates the full welfare losses to exposed campers as it only includes cost of illness and not the diminished value of the trip. Nonetheless, it provides some sense of the magnitude of the welfare impacts from wildfire smoke experienced by campers on public lands.

4. Discussion

Increases in the popularity of outdoor recreation and increases in visitation to western public lands in the United States are coinciding with another trend: the rising number and size of wildfires. Our study, which merged detailed daily camping data at 1069 western campgrounds with spatial wildfire, smoke plume, and air quality data over a 10-year period, documents the extent of the impacts nearby actively burning wildfires and wildfire smoke have on outdoor recreation in the region, and provides causal estimates for how outdoor recreationists respond to fires and smoke. Importantly, we provide the first estimates of wildfire smoke impacts on recreation on public lands across the continental western United States. Smoke, which disperses over great distances, affects many more people than fire itself. We calculated that 383,000 camper-days per year, on average, took place under adverse smoke conditions, or 4% of all camper-days. Using monthly visitation data for the 27 national parks in our sample, we scaled the camping results and estimated that approximately one million national park visitor-days per year, on average, were potentially affected by smoke over the 10-year sample period. As our data exclude a few national parks in the region, this is likely to be an underestimate of the full effects of smoke on national park visitors.

We found that campground use declines in response to fire and smoke. The magnitudes of the estimated adjustments were relatively small, however. Average occupancy rates, for example, decline by 6.4 percentage points for a fire within 20 km and only 1.3 percentage points for adverse smoke conditions. Effects on recreation site use on particularly threatening days (when a fire is very close by or air quality is especially poor) are likely to be greater. Moreover, measurement error may bias these estimated effects downward to some extent. Campers may change their plans without cancelling their reservations, so that we are counting some visits that do not occur. We feel that the magnitude of this error is likely to be small, however, as we observe cancellations in the data and the refund policy provides a financial incentive to cancel.

The minimal effects of fire and smoke on campground usage may be a consequence of constraints on either vacation times or campground availability. As shown in Walls et al. (2018), it is challenging to find an open campsite at many national parks in the peak summer months, so cancelling a trip because of smoky conditions may mean foregoing the entire season. Indeed, we find that the effect of smoke on the average occupancy rate is attenuated in the most popular campgrounds (Table 5).

Unfortunately, this lack of behavioral response by campers may mean significant exposure to poor air quality. The contribution of wildfire smoke to $PM_{2.5}$ concentrations in the United States has increased substantially since about the mid-2000s, now accounting for approximately half of overall $PM_{2.5}$ exposure in the western United States (Burke et al., 2021). The literature finds consistent evidence of an association between wildfire smoke and general respiratory health effects, especially exacerbation of asthma and chronic obstructive pulmonary disease, as well as an association between smoke and increased risk of respiratory infections and all-cause mortality (Reid et al., 2016; Cascio, 2018). Because camping involves extended time outdoors and is often accompanied by strenuous activities, such as hiking, recreational campers are likely to be particularly at risk of health impacts in smoky conditions. Some studies have found that the negative health effects of elevated levels of air pollution can offset the benefits of exercise (Korrick et al., 1998; Guo et al., 2020).

In addition to health impacts, smoke can cause haze and reduced visibility. For visitors to scenic public lands in the western United States, especially signature national parks, such as Grand Teton, Glacier, and the Grand Canyon, reduced visibility can significantly lower the value of the visit. Stated preference survey studies of visibility in national parks have found that improved visibility is highly valued (Rowe et al., 1980; Schulze et al., 1983). One study found that survey respondents would pay about $120 per year in the southeastern United States and about $80 per year in the Southwest for visibility improvement programs that would remove the 20% worst visibility days (Boyle et al., 2016). A separate study in southwestern British Columbia found that survey respondents were willing to pay $92–$112 per year per household (in 2002 Canadian dollars) for a 5–20% improvement in visual range (Haider et al., 2019). The authors apply these estimates to the number of poor visibility days due to wildfire in July and August of each year from 2002 through 2018 and calculate that the value of improving those days from “poor” to “excellent” would total $120 million over the 17-year period.

US federal land management agencies could consider several policies to reduce the impacts that wildfires and associated smoke have on outdoor recreation. These policies can focus on lowering the threat of fire or increasing the ability of outdoor recreationists to adapt. Lowering the threat can be achieved through mechanical thinning of forests, prescribed burns, and managed wildfires (Kalies and Kent, 2016). These activities work in areas where heavy fuel loads have contributed to increasing wildfire activity. Although prescribed burns and managed wildfires produce smoke, they can be used opportunistically during times of the year with minimal impacts on human activities, including outdoor recreation. Prescribed burns also reduce future wildfire activity (Cochrane et al., 2012). While these land management strategies are routinely used by agencies to reduce wildfire hazard, their pace and scale needs to increase dramatically to result in substantial reductions in wildfire hazards and impacts to recreationists and the regions outdoor recreation economy (Clavet et al., 2021).

Adaptation can take the form of shifts in the location and timing of visits to public lands to reduce exposure. To encourage these behavioral adjustments, recreationists may need a “nudge.” As one example, land managers could employ flexible pricing strategies across peak and nonpeak camping seasons by region that could be coupled with other incentives to visit less fire- and smoke-prone locations during peak fire season. In addition, increasing the supply of campsites in less risky locations could help. With wildfires predicted to increase with climate change and outdoor recreation on public lands more popular than ever, policymakers will need to devise creative strategies to both reduce the likelihood and severity of fires and mitigate their impacts on outdoor recreationists.

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Jacob Gellman: Conceptualization, Methodology, Formal analysis, Data curation, visualization, Writing – original draft, Writing – review & editing. **Margaret Walls**: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Matthew Wibbenmeyer**: Conceptualization, Methodology, Formal analysis, Data curation, visualization, Writing – original draft, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2021.110633.

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