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Contrasting prescription burning and wildfires in California Sierra Nevada national parks and adjacent national forests

Jon E. Keeley[A,B,D], *Anne Pfaff*[A] *and Anthony C. Caprio*[C]

[A]US Geological Survey, Western Ecological Research Center, Sequoia–Kings Canyon Field Station, Three Rivers, CA 93271, USA.
[B]Department of Ecology and Evolutionary Biology, University of California, Los Angeles, CA 90095, USA.
[C]Science and Natural Resource Management, Sequoia–Kings Canyon National Parks, Three Rivers, CA 93271, USA.
[D]Corresponding author. Email: jon_keeley@usgs.gov

Abstract. History of prescription burning and wildfires in the three Sierra Nevada National Park Service (NPS) parks and adjacent US Forest Service (USFS) forests is presented. Annual prescription (Rx) burns began in 1968 in Sequoia and Kings Canyon National Parks, followed by Yosemite National Park and Lassen Volcanic National Park. During the last third of the 20th century, USFS national forests adjacent to these parks did limited Rx burns, accounting for very little area burned. However, in 2004, an aggressive annual burn program was initiated in these national forests and in the last decade, area burned by planned prescription burns, relative to area protected, was approximately comparable between these NPS and USFS lands. In 1968, the NPS prescription burning program was unique because it coupled planned Rx burns with managing many lightning-ignited fires for resource benefit. From 1968 to 2017, these natural fires managed for resource benefit averaged the same total area burned as planned Rx burns in the three national parks; thus, they have had a substantial impact on total area burned by prescription. In contrast, on USFS lands, most lightning-ignited fires have been managed for suppression, but increasing attention is being paid to managing wildfires for resource benefit.

Keywords: lightning-ignited fires, fires managed for resource benefit, prescribed natural fires, Rx burns.

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Introduction

Historically, fire has played an essential ecosystem role on Sierra Nevada landscapes (Kilgore 1973). Fire-scar dendrochronology studies show that before Euro-American occupation, many of these forests experienced fires at intervals from 10 to 30 years and these were obviously low-intensity surface fires, evident by the fact that the trees survived to leave a fire-scar record (Wagener 1961; Kilgore 1981; Caprio and Swetnam 1995; Safford and Stevens 2017). These studies also show that in many cases this 'natural' fire regime was interrupted beginning in the late 19th century by cessation of Native American burning, livestock grazing and state and federal suppression of natural lightning-ignited fires (Kilgore and Briggs 1972). Owing to the low-intensity surface fire nature of these fires, suppression was highly successful and thus fire has been excluded from many forests for a century or longer (Skinner and Chang 1996; Safford and van Water 2014).

There are numerous ecosystem impacts of fire exclusion, including effects on tree regeneration, biogeochemical cycling, pathogens, forest structure and fuel accumulation (Parsons and DeBenedetti 1979). One outcome critically important to fire hazard is the accumulation of understorey dead leaves and branches with the potential for altering fire regimes. After a century of fire exclusion, understorey fuel loads from surface litter and ingrowth of saplings have increased many fold (Keifer 1998; Cansler *et al.* 2019). These changes in fuel volume and structure have increased the likelihood of surface fires being carried into the canopy and leading to high-intensity crown fires (McKelvey and Busse 1996; Rothman 2005; Steel *et al.* 2015). While patches of high severity have always played a role in maintaining some plant communities in the Sierra Nevada, such as montane chaparral (Nagel and Taylor 2005), the number and size of high-severity fires are increasing, resulting in conversion of historically forested landscapes to shrubland (Miller *et al.* 2009).

Prescribed (Rx) burning is a management practice that reduces fuels and potentially lessens the impact of wildfires by burning under a narrow range of weather conditions conducive to fire control (Haase and Sackett 1996; Keifer and van Wagtendonk 2006; Keeley *et al.* 2009; Hunter and Robles 2020). This is evident in the markedly different seasonal distribution of Rx and wildfires (Ryan *et al.* 2013). Prescription burning has been experimented with for a long time across the USA (Pyne *et al.* 1996; Rothman 2005). In California forests, Sequoia and Kings Canyon national parks initiated the practice in 1968 with Rx burns in Sierran mixed-conifer forests, and this is considered the oldest program of its kind in the United States because of the combination of Rx burning and managing lightning-ignited fires for resource purposes (Bancroft *et al.* 1985).

This Rx program was a long-delayed response to an early debate on the proper role of fire in these forests. In the early 1900s, Hoxie (1910) wrote a very perceptive article noting, 'The practical invites the aid of fire as a servant, not as a master. It will surely be master in a very short time unless the Federal Government changes its ways by eliminating the theoretical and grasping the practical.' He and others believed that frequent fires from lightning, aided by Native Americans, kept fuel loads low and reduced the risk of high-intensity crown fires (Hoxie 1910; Olmsted 1911; Bigpine 1919; Kitts 1920; Ogle 1920; White 1920). This 'light burning' or 'Indian burning' policy was based on the belief that it was not possible to keep fire out of the forests and therefore it was best to control the type of fire (Cermak 2005). However, some disputed the validity of this argument and believed that theoretically, it was possible to eliminate fire from Sierra Nevada forests (Greeley 1920). This position was driven in part by belief that much of the fire history of these forests was driven by Native American burning, termed 'Piute forestry' (Graves 1920*a*) and this was no longer a factor. In addition, Greeley and Grave's view was motivated by an interest in timber production, and since understorey burning blackened tree bases, reducing timber value, and reduced tree density, such burning was considered counterproductive to timber production (Boerker 1912; Graves 1920*b*; Reddington 1920; Show and Hammatt 1920; MacDaniels 1924; Show and Kotok 1924).

At this time, the California Forestry Committee (comprising representatives from the US Forest Service (USFS), State Department of Forestry, University of California and various lumber companies) conducted a 3-year experiment with prescribed burning and concluded this was not a practical management approach (Bruce 1923). Thus, suppression of all fires was considered to be the only correct management practice and by the late 1920s, public discussion of the subject faded as total fire suppression was both state and federal policy (Husari and McKelvey 1996). While this attitude of suppression prevailed, a few investigators in western North America continued to report evidence in support of the need for Rx burning (Weaver 1943, 1947; Cooper 1960; Wagener 1961).

For much of the mid-elevation forests of the Sierra Nevada, 20th century suppression was highly successful in putting out fires, resulting in near-total fire exclusion over much of the Sierra Nevada forests that historically burned frequently (Skinner and Chang 1996; Safford and van Water 2014). However, attitudes changed in the 1960s with the National Park Service recognition that fire suppression policy was leading to hazardous fuel conditions that threated forest resources, as pointed out in the 1963 Leopold Report (Leopold *et al.* 1963; Schuft 1973; Parsons 1981). In 1968, Sequoia–Kings Canyon national parks initiated an annual prescription burning program along with a 'let-burn' policy of lightning-ignited fires allowed to burn when they did not pose a threat to resources (Kilgore 1973). The 1968 National Park Service Administrative guidelines made these changes optional for parks (Pyne 2015) and soon after, Yosemite National Park initiated Rx burning and allowed certain natural lightning-ignited fires to burn in order to use them to control fuels (Parsons and van Wagtendonk 1996). This use of natural wildfires for resource purposes has been variously named, with 'prescribed natural fire' being widely used (Gilbert 2016), but the Federal Wildland Fire Policy has replaced it with 'managed wildfire for resource benefit' (Berger *et al.* 2018).

Concerns over fire suppression impacts on fire regimes on USFS lands led to major changes in 1978 (Pyne 2015), initially to changes in the long-held '10am policy' (i.e. fire managers were instructed to utilise all available resources in order to ensure the fire was out by 1000 hours the following day) to one of giving consideration to allowing some fires to burn within watersheds where it could be contained (Husari and McKelvey 1996; Cermak 2005; Husari *et al.* 2006). More recently USFS adopted a new planning rule revising forest plans for most forests operating under 20–30 year-old plans in order to consider opportunities to restore fire adapted ecosystems and restoration, including the use of prescription burning (North *et al.* 2012).

The purpose of the present study was to assess the extent to which prescription burning and managed wildfires for resource benefit have been used and how they compare in terms of area burned and timing relative to wildfires over the past six decades. Federal forest management in the California Sierra Nevada is dominated by two agencies, the Department of Interior National Park Service (NPS) parks and the US Department of Agriculture Forest Service (USFS) forests. Because these parks and forests are managed with very different mandates for utilising forest resources, we have elected to compare the three NPS parks with the six adjacent USFS forests (Fig. 1). In our comparison of wildfires, we have separated out those managed with fire suppression actions from those managed for resource purposes. We also explored how seasonal timing of Rx burning compared with wildfires and to what extent it has changed over the years, and in relationship to climate parameters.

Methods

Study area

We studied fire history on the three NPS parks in the Sierra Nevada in California and the six USFS forests adjacent to these parks (Fig. 1); note: as the Inyo National Forest is split between two mountain ranges, only the western portion was used. NPS and USFS lands differ in several ways. For example, NPS lands are primarily managed for conservation of natural landscapes and recreation whereas the USFS lands are managed for multiple purposes including ecosystem protection as well as resource extraction. Vegetation composition was based on USDA Forest Service (2020) mapping zones. Distribution by 500-m elevation bands was extracted from digital elevation models (Hutchinson and Gallant 2000).

Fire history

Fire history on these lands from 1960 to 2017 was obtained from the Cal Fire FRAP (Fire and Resource Assessment Program) fire history database (Cal Fire 2017). This is a spatially explicit fire perimeter database that is fairly complete for the time period being considered (Syphard and Keeley 2016). Significant additions were made to this database from agency records of

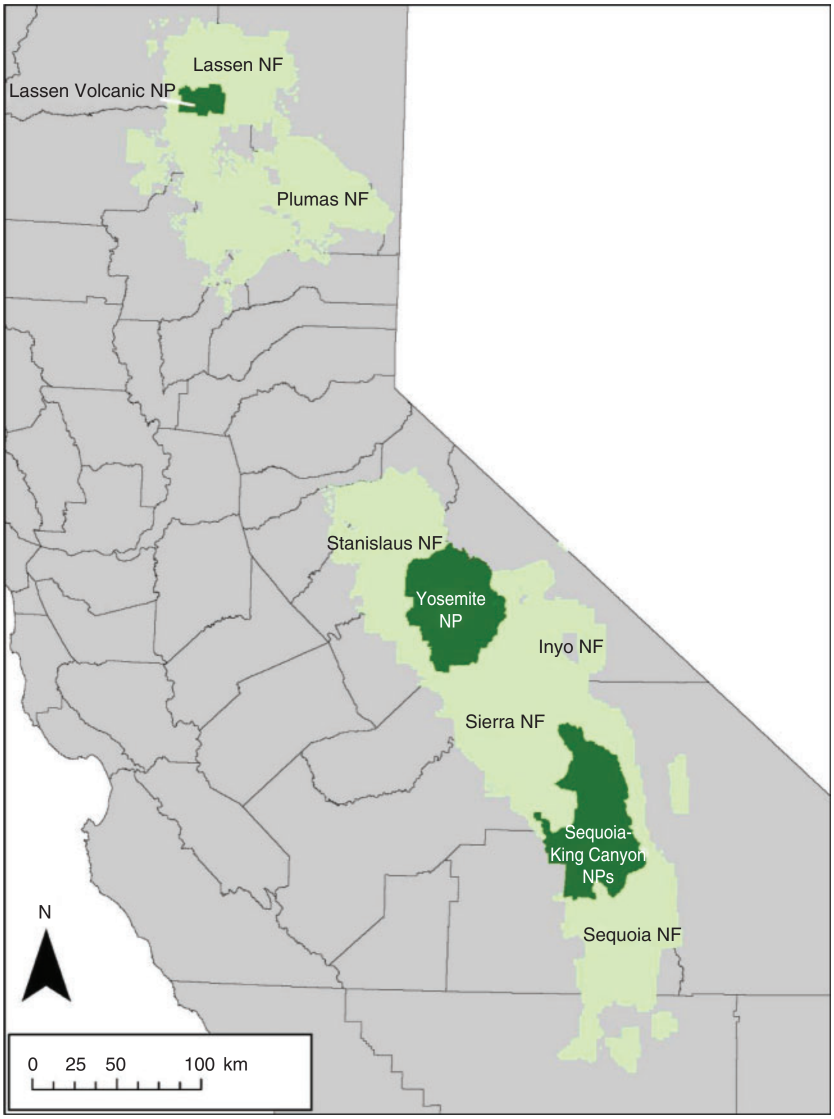

Fig. 1. Map of central and northern California highlighting Sierra Nevada national parks (dark green) and adjacent national forests (light green).

USFS and NPS. We extracted all fires within the boundaries of the nine units being considered, separated by unit and year, and whether human-ignited, lightning-ignited wildfires and planned Rx burns as well as lightning fires that were managed for resource purposes, known as 'managed wildfires for resource benefit' (Berger *et al.* 2018). Data were normalised by the available vegetated landscape in each of the units.

Data on start date and end date of each fire were also collected from this database. These dates were represented by the Julian day of the year, with 1 January being day 1 and 31 December being day 365, or 366 in leap years. Start date and duration of the fires were compared between NPS and USFS lands for both human-ignited and lightning-ignited wildfires and planned Rx fires. There were several significant problems with the start dates recorded in the FRAP database for Rx burns on USFS national forests, with several fires having start dates many years before the end date, presumably representing date of initial planning rather than ignition dates (H. Safford, pers. comm., 5 April 2020). For these fires, start dates were not included in our data analysis. Also, by comparing the FRAP data with NPS data, it was found that some NPS fires had end dates in the FRAP database that were control dates and not 'out' dates. This was also a problem with USFS data as it was not always clearly noted if the 'end date' was when the fire was out, or when it was contained and it was determined there was no danger of escape, in which cases subsequent patrols weeks or months later might indicate the official end date (R. Bauer, Forest and Fuels and Prescribed Fire Program, Plumas National Forest, pers. comm., 17 June 2020). In general, extremely long Rx burns of 6 months or more over winter were considered questionable and these points were eliminated for the analysis of end date.

Table 1. Elevation and vegetation characteristics of the NPS parks (dark green in Fig. 1) and adjacent USFS forests (light green in Fig. 1) (based on CALVEG, USDA Forest Service 2020)

NPS or USFS	Unit	Elevation (m)			Barren	Vegetated	Vegetation type (%)			
		Min	Mean	Max	(×1000 ha)		Conifer	Hardwood	Shrubland	Herbaceous[A]
USFS	Sequoia	260	1870	3780	20	426	54	18	22	6
NPS	Sequoia–Kings	400	2850	4410	110	221	75	13	11	1
USFS	Sierra	280	2100	4170	56	470	63	20	11	6
USFS	Stanislaus	250	1730	3520	43	318	68	14	14	4
NPS	Yosemite	650	2450	3980	44	247	85	7	5	3
USFS	Inyo (west)	1150	2750	4410	83	270	55	3	39	3
USFS	Plumas	270	1560	2550	7	476	80	9	9	2
NPS	Lassen Volcanic	1590	2090	3190	5	38	93	1	5	1
USFS	Lassen	270	1610	2650	5	445	74	4	19	3

[A]Includes wetlands.

These parks and forests are variable in size and so all statistical comparisons were normalised by area of vegetated landscape. Restricting the comparison in this way is important because these areas differ markedly in the proportion of barren landscapes (Table 1), which have limited capacity to carry fire. Thus, all data were normalised to the extent of burnable (vegetated) landscape area using CALVEG data (USDA Forest Service 2020).

Comparisons between the nine units were made with ANOVA after verifying data were appropriate for this parametric analysis. Bonferroni post-hoc tests were run to evaluate which of the multiple comparisons were significant. Comparisons between NPS and USFS lands were made with two-sample *t*-tests. Linear regression analysis was done on variables shown to be independent and with no evidence of autocorrelation, using an intercept constant and presenting the adjusted r^2 value.

To evaluate climate effects on fire activity, we used PRISM climate data. For every year in the analysis, we extracted 2.5 arc-minute PRISM data (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 15 January 2018) for areas within the boundaries of the study region. For each region and year, we computed area-weighted averages of monthly mean precipitation and temperature within each forest. Palmer Drought Severity Indices were taken from NOAA (2018).

Results

Fire history

For these landscape units (Fig. 1), the USFS forests were generally at lower elevations (Table 1) and more broadly distributed across a wider range of elevations than NPS parks (Fig. 2). All national parks and national forests were dominated by conifer forests, though the former, which were at somewhat higher elevations, had greater conifer composition (Table 1).

Annual area burned by wildfires illustrated marked differences between forests and parks (Fig. 3). On USFS lands, the national forests with the highest years of wildfire activity were the Sequoia (Fig. 3*a*) and Stanislaus (Fig. 3*d*) forests. High years were also seen in NPS Yosemite (Fig. 3*e*) and Lassen Volcanic (Fig. 3*h*) national parks. Lowest wildfire activity was observed in Sequoia–Kings Canyon (Fig. 3*b*) national parks and the high-elevation Inyo forest (Fig. 3*f*).

Across the entire 58-year period under consideration, lightning-ignited fires accounted for most wildfires in Sequoia–Kings Canyon national parks and in Yosemite National Park, and in these parks, area burned by lightning fires was over double that caused by human-ignited fires (Table 2). The percentage of wildfires due to lightning was highly correlated with elevation across the nine units ($r^2 = 0.72$, $P = 0.004$). This elevational effect was very pronounced in Sequoia–Kings Canyon and Yosemite national parks, where areas burned by human ignitions were at markedly lower elevation than lightning-ignited fires (Supplementary Fig. S1). This was true for a couple of the forests as well but was not a universal pattern. Except for the Inyo National Forest, humans were the dominant source of wildfires on the other five USFS forests considered here. Although most wildfires were suppressed, a sizeable number were not and they were allowed to burn for resource purposes. These fires were classified as wildfires managed for resource benefit and all were lightning-ignited fires (Table 2).

History of prescription burning

Prescription burning began in Sequoia National Park in 1968 (Fig. 4*b*) and these planned Rx burns have been conducted every year up to the present. Rx burns began in 1970 in Yosemite National Park and have continued most years since then (Fig. 4*e*). For the next 35 years, the parks dominated the prescription burning on federal lands in the Sierra Nevada. Prescription burning on the six USFS forests considered here began in the 1970s and although over 30 Rx burns were recorded before 2000, they accounted for relatively little area burned. In the late 1990s, there was a 5-year hiatus in Rx burning on these USFS forests, followed by more or less annual prescription burning beginning in 2004 (Fig. 4*a*, *c*, *d*, *f*, *g*, *i*).

On both NPS and USFS lands, planned Rx burning averaged less area burned than wildfires (Table 2). However, on all parks and forests, there was at least 1 year where prescription burning exceeded wildfires, with this occurring in 25 years in Sequoia–Kings Canyon and 14 years in Yosemite (data not shown). The annual use of Rx burning in Sequoia–Kings Canyon and Yosemite is recorded in the relatively low year-to-year variance reflected in the coefficient of variation (CV; Table 2). Across all nine units, there was a highly significant relationship ($r^2 = 0.74$,

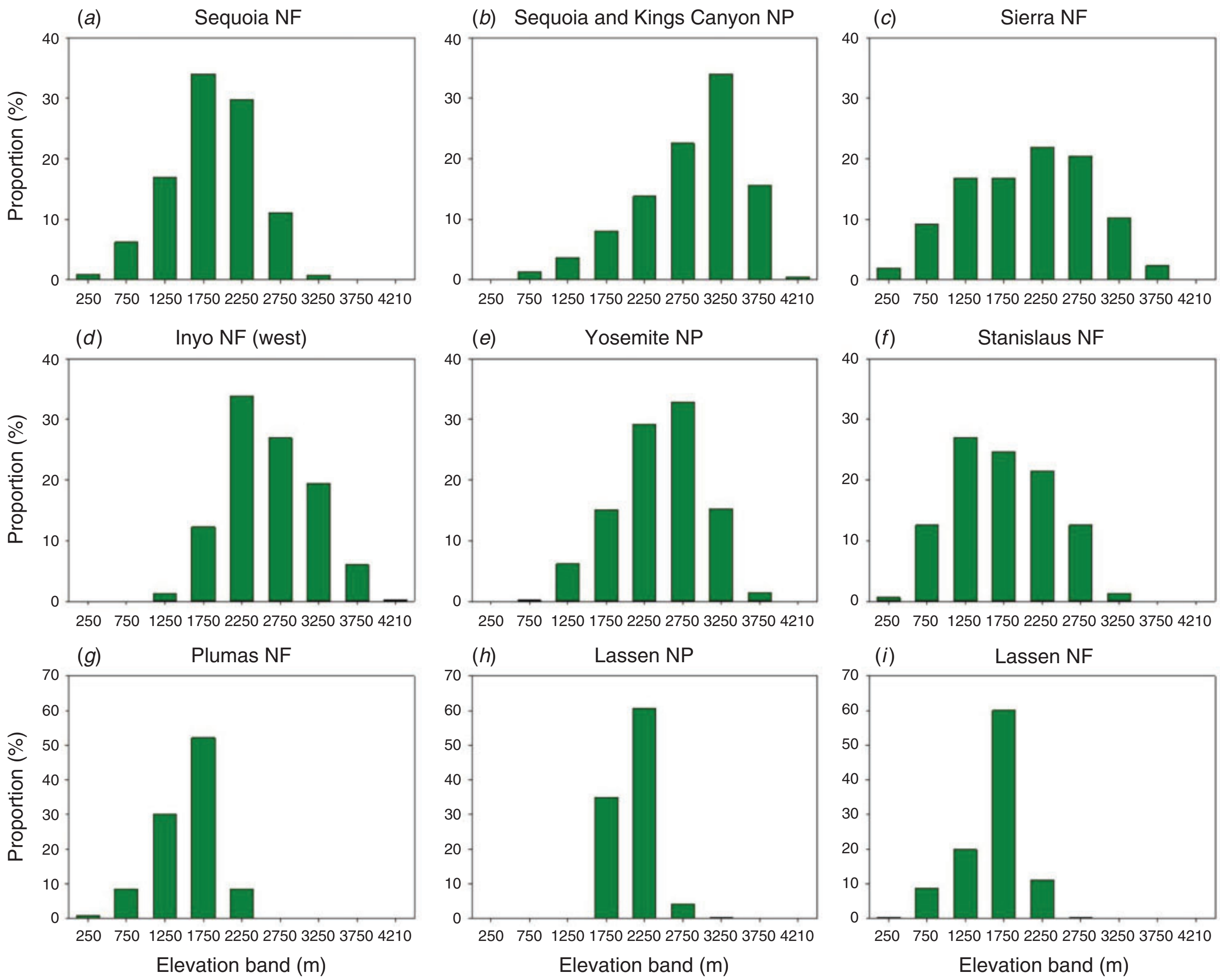

Fig. 2. Elevational distribution of landscapes in the three national parks (*b*, *e*, *h*) and adjacent national forests (*a*, *c*, *d*, *f*, *g*, *i*).

$P = 0.003$) between conifer cover (Table 1) and area burned by prescription (Table 2).

Fires often reburned previously burned areas and the level of reburning represented by these burn statistics is shown in Table 3. Thus, the total landscape burned is reduced by this percentage of reburning. What stands out in these comparisons is that a greater percentage of area reburned was from lightning-ignited fires on NPS lands (Table 3). With respect to both NPS and USFS lands, prescription burning comprised a similar percentage of reburning, from ~10 to 20%; the main exception was Yosemite with nearly 30% of their Rx burning being reburns.

Over this 58-year period, the three national parks had the highest proportion of Rx burning, generally several times more area (relative to the land area in the jurisdiction) annually than the adjacent national forests (Fig. 5*a*). However, in the last 10 years, the national forests caught up and generally matched the Rx burning in the national parks (Fig. 5*b*).

The total area burned by prescription comprises both the Rx burns and those wildfires managed for resource benefit (Table 2). Across the 58 years of record, the three national parks had a substantial contribution to prescription burning from lightning-ignited fires managed for resource benefit, and in fact these unplanned wildfires averaged approximately the same area burned as planned Rx burns. Owing to the late initiation of regular Rx burning on all USFS forests (Fig. 4), and limited or lack of managing lightning ignitions for resource benefit, national forests had substantially less total area burned by prescription than adjacent parks (Table 2).

Timing and duration of prescription burning

Comparison of seasonal timing of wildfires and Rx burns showed some subtle differences in distribution of start dates (Fig. 6). On NPS lands, wildfires tended to be concentrated between July and September, i.e. Julian days 200–290 (Fig. 6*a*) whereas they were more broadly distributed on USFS lands from May to October (Fig. 6*c*). Over the 58-year period, start dates of wildfires did not show any significant change on either NPS or USFS lands. Initiation of Rx burns changed significantly over time on NPS lands, with more early spring burns in recent years (Fig. 6*b*). On USFS lands, since the spike in Rx burning in the early 2000s, Rx burns were conducted throughout much of the year, ranging from April to October (Fig. 6*d*).

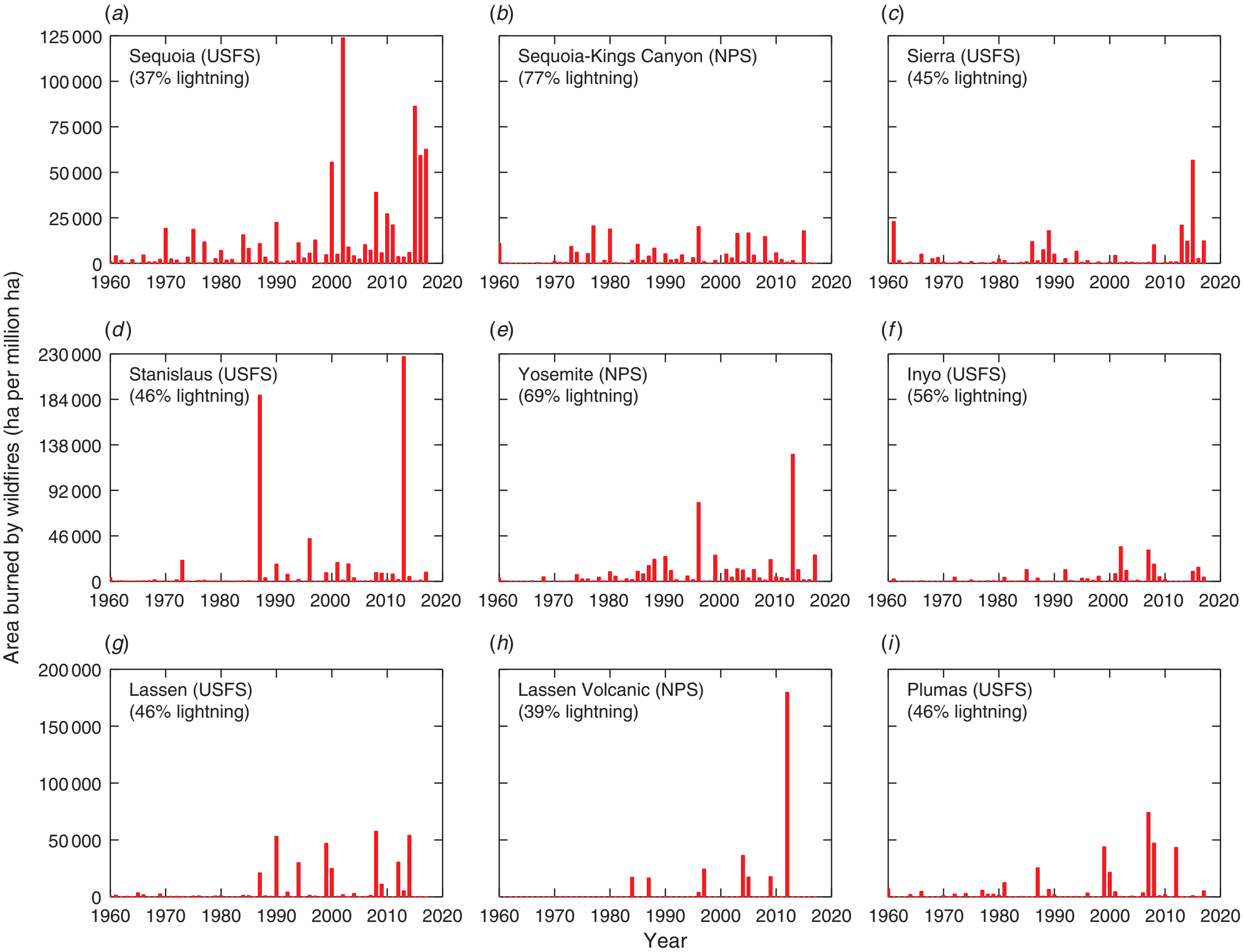

Fig. 3. Area burned by wildfires normalised by the vegetated area within each unit: three national parks (*b*, *e*, *h*) and six national forests (*a*, *c*, *d*, *f*, *g*, *i*).

Comparing across individual parks and forests, there was no significant difference in start dates for lightning-ignited fires (Table 4). For human-ignited fires, the only significant differences (based on the Bonferroni post-hoc test) were between the earliest average start date on the Inyo and Sequoia forests *v*. the two latest dates for Sequoia–Kings Canyon and Yosemite. For Rx fires, the earliest average date was for the Lassen forest and it was significantly different from the three latest dates for Lassen Volcanic park, Sequoia–Kings Canyon park and Sequoia forest.

Duration of wildfires exhibited significant differences across the nine units. There was a highly significant difference in duration of lightning-ignited fires, with the three NPS parks having significantly longer fires than adjacent forests (Table 4). On NPS lands, some of the longest-lasting Rx burns were early season ignitions (Fig. 7*a*) but this was not the case on USFS lands (Fig. 7*b*). The average duration of burning varied significantly across the nine units for all sources of ignition (Table 4). Based on the Bonferroni post hoc test, lightning-ignited fires were significantly longer in duration on the three national parks, ranging from 60 to 75 days, than on the Stanislaus, Inyo, Plumas and Lassen national forests, which ranged from 8 to 13 days. In contrast, human-ignited fires were relatively short in duration on eight of the nine units, ranging from 6 to 14 days. With respect to wildfire duration, there was a significant increase in the length of wildfires over the 71-year period on both NPS (Fig. 8*a*) and USFS (Fig. 8*c*) lands, but no significant change in the duration of prescription burns (Fig. 8*b*, *d*).

Average duration of Rx burns varied most between subregions, being substantially longer in the south for both NPS and USFS lands (Table 4). Owing to issues of reporting end dates of Rx burns discussed in the methods, we also report the most common or modal frequency length of Rx burns. In nearly all units, 1 day was the mode for the length of Rx burns (Table 4), with 2 days a close second.

Climate drivers of fire activity

Multiple regression analysis of temperature, precipitation and Palmer Drought Severity Index (PDSI) did show highly significant relationships with both area burned by wildfires and by prescription (Table 5). Temperatures in certain summer and autumn months showed a positive relationship with wildfire area burned on both NPS and USFS lands, and drought (measured by PDSI or spring precipitation) had negative effects. Climate was also correlated with area burned by prescription.

Table 2. Area burned by wildfires ignited by humans or lightning managed for suppression or managed for resource benefit, planned prescription burns and prescribed natural fires (lightning-ignited fires managed for resource benefit) for the years 1960–2017

$\bar{X}$, mean; CV, coefficient of variation; within-row values with the same letter were not significantly different based on the Bonferroni post-hoc test, differences for column values based on the Bonferroni are described in the text

		Fire frequency (No. per million ha per year)				Area burned (ha per million ha per year)					
		Wildfires			Prescription	Wildfires			Prescription		Total of prescribed + resource benefit burning
		Total		Managed for resource benefit		Total		Managed for resource benefit			
NPS or USFS	Unit	Human $\bar{X}$	Lightning $\bar{X}$	$\bar{X}$	$\bar{X}$	Human $\bar{X}$ (CV)	Lightning $\bar{X}$ (CV)	$\bar{X}$ (CV)	$\bar{X}$ (CV)	*P*	$\bar{X}$
USFS	Sequoia	10.5	5.3	0.5	5.2	7864 (2.4) a	4530 (2.8) a,b	444 (3.7) b	319 (4.4) b	0.010	763
NPS	Sequoia–Kings	3.7	12.7	7.3	22.9	903 (3.1)	3094 (1.7) a	2409 (1.8) a	2265 (1.4) a	0.009	4673
USFS	Sierra	5.2	2.3	0.2	4.4	2128 (2.1)	1734 (4.1)	125 (6.7)	326 (2.8)	0.118	451
USFS	Stanislaus	9.4	4.4	0.8	6.8	5784 (5.1)	4855 (1.9)	377 (5.7)	395 (2.4)	0.387	772
NPS	Yosemite	7.7	23.5	8.8	14.2	2764 (6.1)	6094 (1.9)	2398 (1.6)	1599 (1.4)	0.112	3998
USFS	Inyo (west)	2.7	3.2	0.3	5.4	1396 (3.2) a	1937 (2.7) a	101 (6.5) b	343 (2.5) b	0.040	194
USFS	Plumas	4.2	3.5	0	7.9	3499 (2.8) a	2188 (3.5) a,b	0 (–) b	266 (2.2) b	0.050	266
NPS	Lassen Volcanic	1.4	5.5	2.7	10	3268 (7.2)	2125 (3.2)	1545 (3.8)	1910 (3.9)	0.869	3455
USFS	Lassen	2.8	1.7	0	7.1	3392 (2.8)	2897 (3.3)	0 (–)	816 (2.2)	0.179	816

On NPS lands, it was negatively affected by drought over the past 2 years but positively affected by winter and spring precipitation in the year of burning. On USFS lands, the area burned by prescription was negatively affected by drought over the past 2 years. On USFS lands, start date of wildfires showed a highly significant negative relationship with autumn precipitation. Start date on NPS lands and duration of burning were only slightly correlated with climate (Table 5).

Discussion

Globally, Rx burning has a long history in many countries and across North America (Biswell 1989, Pyne *et al.* 1996, Rothman 2005, Ryan *et al.* 2013). Our focus in the present paper represents a regional view of Rx burning and recognises that the history of Rx burning in other regions, and with other agencies, is very different than what we cover (Kolden 2019). In California's Sierra Nevada, Sequoia–Kings Canyon and Yosemite national parks are noteworthy in their early initiation of an aggressive Rx burning program. It began in 1968 and was an important step towards restoring fire as an ecosystem process in these forests (Kilgore 1973).

These NPS programs were unique in that they coupled planned prescribed ignitions with managing natural lightning ignitions for resource benefit. The latter, originally termed the 'let-burn' program (Kilgore and Briggs 1972), was later named 'resource objective wildfires' (Meyer 2015) or 'prescribed natural fires' (Gilbert 2016). In 2008, federal terminology was modified to just include 'prescribed fire' and 'wildfire', and these prescribed natural fires are now termed 'wildfires managed for resource benefit' (Berger *et al.* 2018). In addition to changes in terminology, there are undocumented reports that natural fires allowed to burn for resource purposes have been enhanced by human Rx ignitions within the perimeters of these natural lightning fires. In the present study, wildfires managed for resource benefit were fewer in number than Rx burns but owing to their size, they accounted for nearly as much or more area burned by planned Rx burns in Sequoia–Kings Canyon, Yosemite and Lassen Volcanic national parks. The policy of allowing these natural fires to burn for resource purposes (Parsons and van Wagtendonk 1996) has likely played a major role in why these lightning-ignited fires burn far longer in the three national parks than lightning-ignited fires on adjacent national forests.

USFS national forests adjacent to these three national parks also began experimenting with prescription burning soon after initiation of the NPS Rx program. However, for the next three decades, Rx burns were infrequent and generally very small (often just pile burns) so they comprised relatively little area burned on these six forests. Thus, over this 58-year period, the three national parks greatly outpaced the adjacent national forests in planned Rx burns. However, in 2004, planned Rx burns took on a new life in the national forests and contributed a significant area burned most years; thus, in the last decade of our study, Rx burning was approximately comparable between NPS and USFS lands.

Three issues that need addressing are: (1) what are the factors, biophysical and policy-related, that can account for the temporal differences in commitment to Rx burning by these national parks and adjacent national forests, both for planned

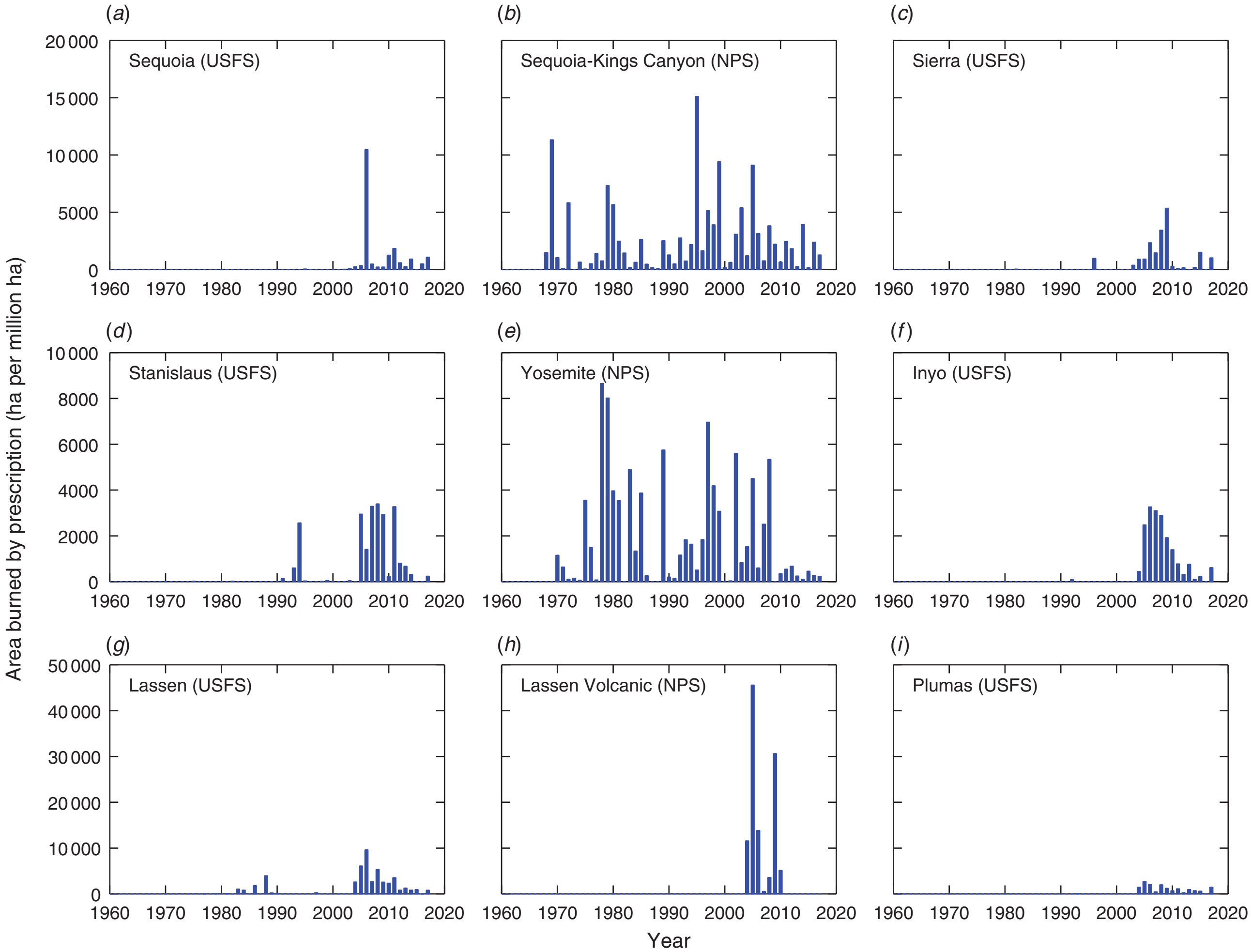

Fig. 4. Area burned by planned prescription burns normalised by the vegetated area within each unit: three national parks (*b*, *e*, *h*) and six national forests (*a*, *c*, *d*, *f*, *g*, *i*).

Table 3. Percentage area reburned by wildfires ignited by humans or lightning and planned prescription burning (1960–2017)
In some cases the same area may have burned more than twice

NPS or USFS	Unit	Human (%)	Lightning (%)	Prescription (%)
USFS	Sequoia	15	7.2	12.4
NPS	Sequoia–Kings	7.8	12.9	18.9
USFS	Sierra	11.6	9.7	18.8
USFS	Stanislaus	10.3	16.3	8.1
NPS	Yosemite	2.2	21.7	28.8
USFS	Inyo (west)	2.9	0.8	14.3
USFS	Plumas	6.6	3.5	17.1
NPS	Lassen Volcanic	0.6	13.2	19.6
USFS	Lassen	11.9	6.1	11.6

ignitions and wildfires managed for resource benefit? (2) How effective has Rx burning been? And (3) what are the constraints to utilising planned and prescribed natural burns?

In contrasting patterns on NPS lands with USFS lands, a point to begin with is the different management goals. A major mandate for NPS parks is retaining natural ecosystem processes and the Leopold Report (Leopold *et al.* 1963) articulated an idea that was gaining strength at the time that fire was a natural ecosystem process. This was a factor leading to the use of planned Rx burns coupled with management of natural lightning fires to restore fire to these landscapes (Kilgore and Briggs 1972). This new thinking met with some resistance. In Sequoia–Kings Canyon park, public outcry about the black bark on giant sequoias led to a short-lived moratorium on Rx burning in 1986 and appointment of a special task force to evaluate NPS's use of prescription burning (Rothman 2005). The final conclusions, referred to as the 'Christensen Report' by Parsons and van Wagtendonk (1996), were in support of the Sequoia–Kings Canyon Rx program but recommended thorough monitoring of fire effects. The massive Yellowstone fires of 1988 raised public concerns about fire and also led to a short-term moratorium on Rx burning in Yosemite and other national parks (van Wagtendonk pers. comm., June 2020).

Department of Agriculture USFS mandates are broader than those of the NPS and address multiple needs of more

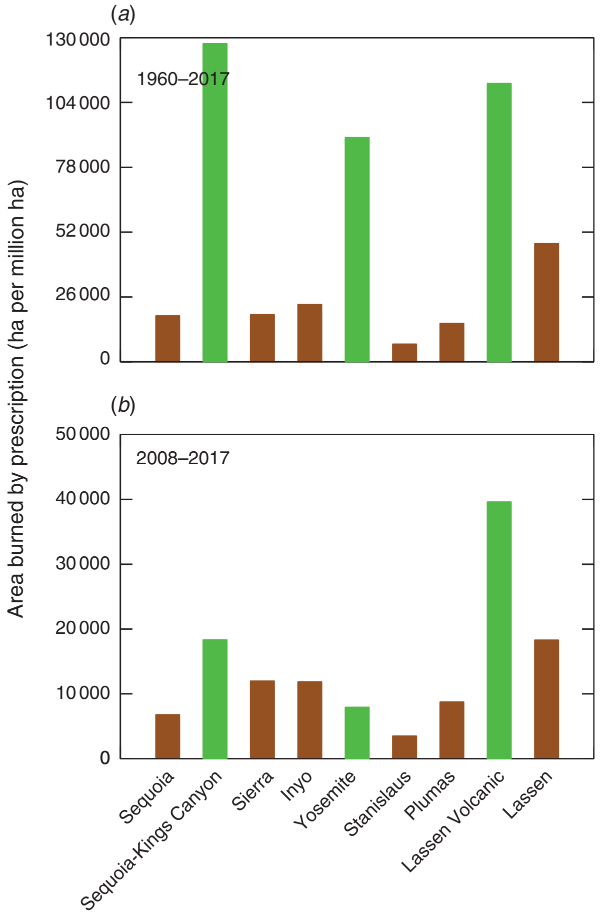

Fig. 5. Area burned by planned prescription burns for the period (*a*) 1960–2017, and (*b*) 2008–2017 for the three national parks (green) and adjacent national forests (brown).

stakeholders. Although restoring natural ecosystem processes has long been understood as an important goal, early emphasis was on reducing fire hazard that could destroy timber resources (Mutch 1997). However, it has long been recognised that this can be accomplished with the use of mechanical thinning of forests (Schwilk *et al.* 2009, Safford *et al.* 2012, North *et al.* 2015*a*), which is an acceptable alternative to prescription burning on USFS lands, but not something that was compatible with restoring natural ecosystem processes on NPS lands. Reliance on mechanical treatments of fuels contributed to the limited use of Rx burns from 1972 to 1998 on these USFS lands, which resulted in very little area burned and they are reasonably interpreted as experimental. However, in 1998, according to the FRAP database, there was a 5-year cessation of all Rx burning on these USFS lands. This followed completion of the Sierra Nevada Ecosystem Project in 1996 that led to the Secretary of Agriculture chartering a study of how well science was incorporated into the development of management options (USDA Forest Service 1998). The outcome was the Sierra Nevada Conservation Framework (Pyne 2015) and in 2004, Rx burning continued on an annual basis on these Sierra Nevada national forests. Several factors account for this renewed interest in Rx burning, including greater efficiency of Rx burns on steep terrain and less severe impacts on soil structure relative to mechanical treatments (North *et al.* 2015*a*), and reduced costs of burning when the goal is to reduce ingrowth from ladder fuels, a treatment that has limited commercial value (Schwilk *et al.* 2009). Additionally, a national comparison of mechanical treatments with prescription burning showed that the former was not an appropriate surrogate for restoring many ecosystem processes requiring fire (McIver *et al.* 2013)

Historical changes in fire policy have most certainly been influenced by biophysical characteristics that influence fire activity. For example, the widespread management of wildfires for resource benefit in Sierra Nevada national parks contrasts with the total lack of such management fires on some national forests (Table 2) and is likely tied to elevational differences that drive vegetational differences (Table 1). The policy of managing wildfires for resource benefit in Sequoia–Kings Canyon was primarily, but not entirely, for high-elevation lighting-ignited fires, as these lower-biomass forests are inherently less of a threat because of their remoteness and are not closely juxtaposed with human resources at risk. USFS forests are more broadly distributed at lower elevations (Fig. 2) and although much of this landscape matches the peak elevation for lightning strikes in the Sierra Nevada (van Wagtendonk and Cayan 2008), national forests generally have a greater proportion of shrublands and woodlands susceptible to crown fires, and thus less conducive to managing lightning-ignited fires for resource purposes.

Evaluating the effectiveness of prescription burning (including both planned ignitions and wildfires managed for resource benefit) can focus on different benchmarks. For example, is there evidence that these burns have altered wildfire impacts or is there evidence that they have returned these ecosystems to a more resilient condition? Another approach is evaluating the extent to which forest ecosystem processes have been restored to conditions before Euro-American influence. National Park Service focus has been on the latter approach as extensive fire histories for these parks have shown the natural fire regimes were greatly altered by fire exclusion during much of the 20th century. Dendrochronology studies show that the historical fire return interval before Euro-American impacts in Sequoia–Kings Canyon ranged from 10 to 20 years in mid-elevation conifer forests but was an order of magnitude longer in higher-elevation forest types (Caprio and Graber 2000). That study used a benchmark of the contemporary departure from this historical interval (Fire Return Interval Departure, FRID) to evaluate how the prescription burn program was doing. Evaluating the first 30 years of the prescription burning program showed that the burn program was having a substantial positive effect, but still fell far short of what would be required to return these mid-elevation forests to within their historical range of variation. This analysis suggested a need to more than double the prescription burning area treated annually to approach historical fire return intervals. Similar conclusions apply to forests throughout the western USA (Schoennagel and Nelson 2011, North *et al.* 2012).

There are numerous constraints to Rx burning. These include air-quality restrictions that limit the temporal window of opportunity for burning placed by regional air quality control agencies, appropriate weather conditions of wind speed and relative humidity that are required for controlling burns, varying standards between agencies in legal compliance, and availability of personnel for conducting the burns, which is commonly limited

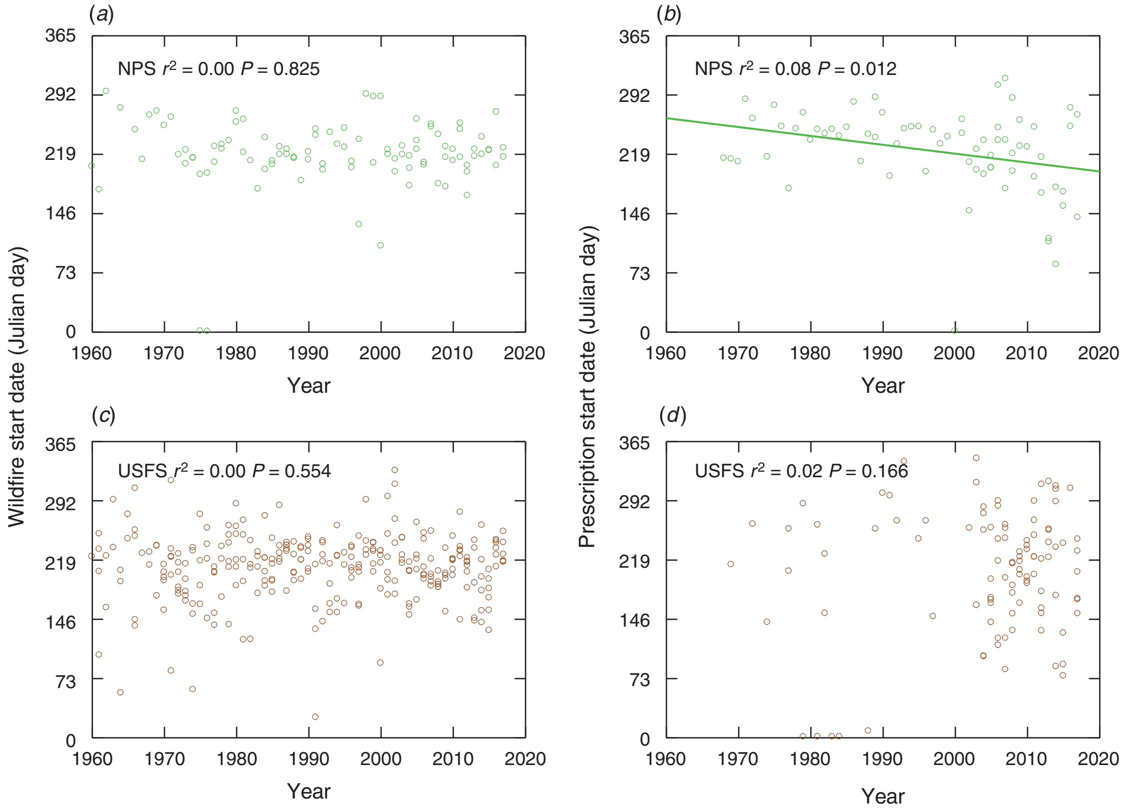

Fig. 6. Historical patterns of start date for wildfires (*a*, *c*), and for planned prescription burns (*b*, *d*) on national parks (*a*, *b*), and national forests (*c*, *d*).

Table 4. Start date and duration for wildfires ignited by lightning or humans and prescription burning (1960–2017)

$\overline{X}$, mean; CV, coefficient of variation. Within-row values with the same letter were not significantly different based on the Bonferroni post hoc test, differences in column values are presented in the text

		Start date (Julian day)				Duration (days)				
NPS or USFS	Unit	Humans $\overline{X}$ (CV)	Lightning $\overline{X}$ (CV)	Prescription $\overline{X}$ (CV)	*P*	Humans $\overline{X}$ (CV)	Lightning $\overline{X}$ (CV)	Prescription $\overline{X}$ (CV)	*P*	Prescription Modal days (%)
USFS	Sequoia	200 (0.14) a	205 (0.16) a	247 (0.18)	<0.001	7 (1.4)	25 (1.3)	41 (1.0)	<0.001	1 (44)
NPS	Sequoia–Kings	235 (0.22)	223 (0.11)	224 (0.21)	0.332	14 (1.6)	60 (0.6) a	45 (0.7) a	<0.001	1 (11)
USFS	Sierra	211 (0.20)	215 (0.14)	216 (0.34)	0.900	6 (1.4)	34 (1.0) a	43 (1.1) a	<0.001	1 (35)
USFS	Stanislaus	210 (0.25)	219 (0.14)	208 (0.27)	0.441	8 (1.5)	12 (2.8)	10 (1.8)	0.123	1 (67)
NPS	Yosemite	240 (0.19)	203 (0.28)	202 (0.29)	0.069	6 (0.6) a	63 (0.6)	13 (1.5) a	<0.001	1 (21)
USFS	Inyo (west)	193 (0.31)	211 (0.14)	207 (0.35)	0.414	9 (1.3)	13 (2.3)	10 (1.2)	0.061	1 (42)
USFS	Plumas	216 (0.25)	206 (0.18)	195 (0.36)	0.400	7 (1.2)	9 (1.3)	10 (1.4)	0.549	1 (65)
NPS	Lassen Volcanic	202 (0.03)	221 (0.15)	274 (0.16)	0.064	95 (0.3) a	75 (0.4) a	7 (1.7)	0.002	2 (13)
USFS	Lassen	222 (0.20) a	219 (0.13) a	159 (0.36)	0.001	11 (1.5)	8 (1.1)	10 (1.4)	0.769	1 (54)
	P	0.003	0.176	<0.001		<0.001	<0.001	<0.001		

by their involvement in wildfires (Bryan 1997, Quinn-Davidson and Varner 2012, Ryan *et al.* 2013, North *et al.* 2015*b*). Coordinating these limitations provides 'burn windows' through the year that are suitable for prescription burning. An intensive study of these burn windows for the Lake Tahoe Basin in California showed that there were unused opportunities in spring and autumn that could be used to enhance fuel treatments (Striplin *et al.* 2020). Of course, biopolitical considerations necessarily are involved as Rx burning has the potential for attracting attention when extreme fires impact resources. For example, the 1988 Yellowstone fires resulted in a moratorium on Federal fire use that year (Rothman 2005) and this impact is seen in reductions in Rx burning in Sierra Nevada parks. Such events also have very different impacts on different people and of course history is driven by personalities; anecdotal evidence from the fire records suggests periods of aggressive Rx burning

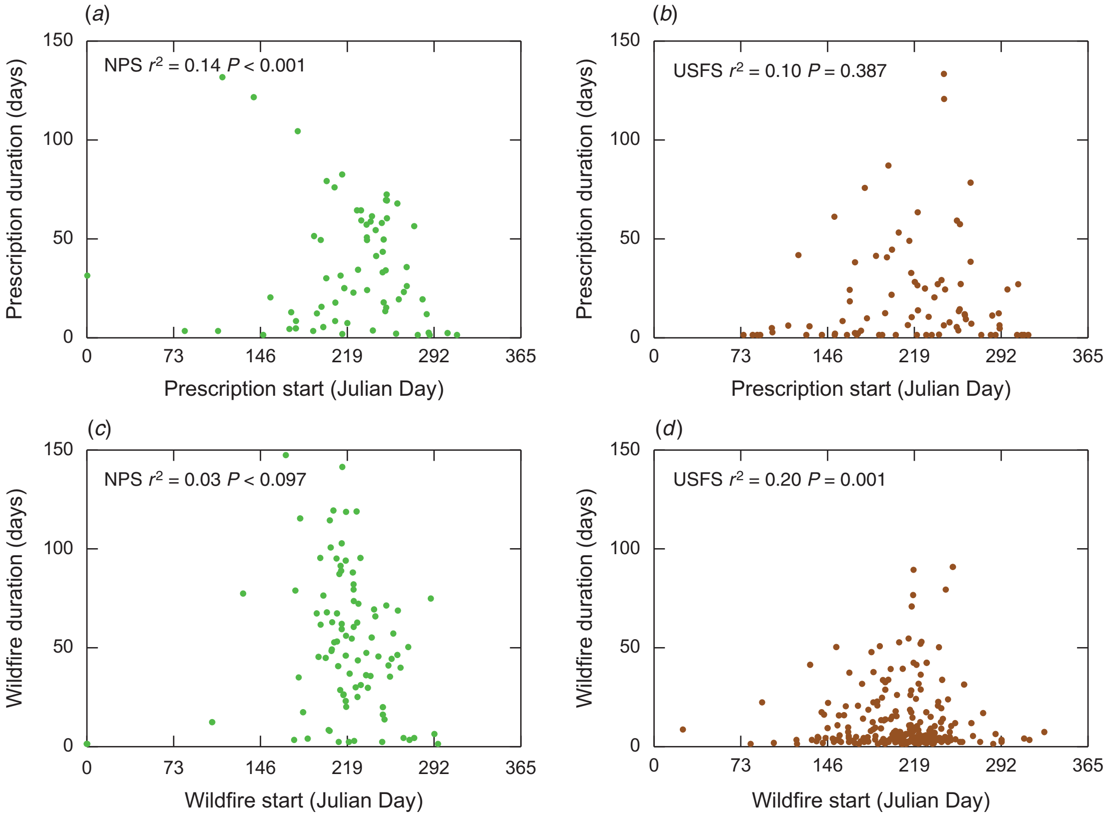

Fig. 7. Duration of fires by start date for planned prescribed burns (*a*, *b*), and wildfires (*c*, *d*) on national parks (*a*, *c*), and national forests (*b*, *d*).

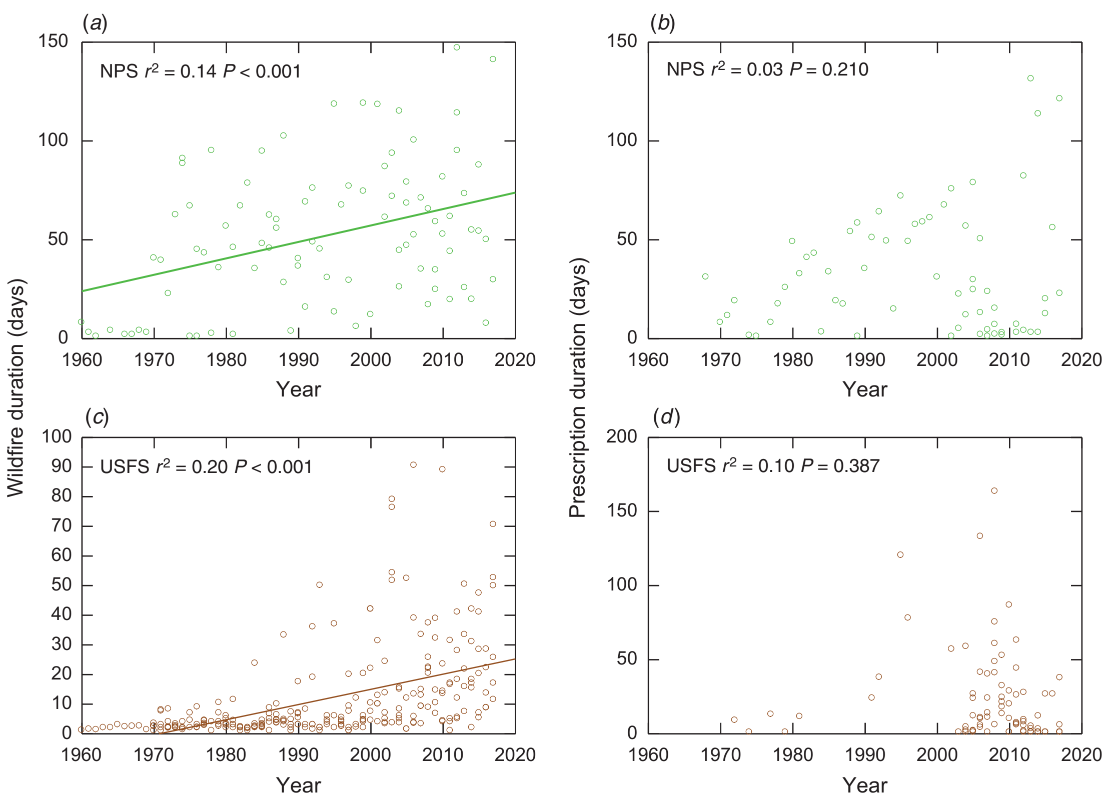

Fig. 8. Historical patterns of wildfire duration (*a*, *c*), and planned prescribed burns (*b*, *d*) for national parks (*a*, *b*), and national forests (*c*, *d*).

Table 5. Climate models for wildfires and prescription burns in NPS parks and adjacent USFS forests
All parameters are normalised to the vegetated area under study. *T*, average temperature; Ppt, precipitation; PDSI, Palmer Drought Severity Index

Area burned by wildfires
NPS: log area = –0.225 + Oct T + July T – 2 years PDSI: adj-r^2 = 0.18 $P < 0.001$
USFS: log area = 0.464 + Jun T + Nov T – Feb T – Spring Ppt: adj-r^2 = 0.15 $P < 0.001$
Area burned by prescription
NPS: log area = 3.456 + Winter–Spring Ppt – 2 years PDSI: adj-r^2 = 0.15 $P < 0.001$
USFS: log area = –102.9 + Jul T – Prior Year Winter-Spring Ppt[A] – 2 years PDSI: adj-r^2 = 0.45, $P < 0.001$
Start date of wildfires
NPS: Julian day = 227.79 + 3 years PDSI: adj-r^2 = 0.07 $P = 0.014$
USFS: Julian day = 490.58 – Nov Ppt – Oct Ppt – Aug T: adj-r^2 = 0.25 $P < 0.001$
Duration of prescription burns
NPS: Duration in days = 6.752 + 2 years PDSI: adj-r^2 = 0.06 $P = 0.030$
USFS: –47.84 – Winter T + Autumn T: adj-r^2 = 0.05 $P = 0.044$

[A]Although it might be expected that winter–spring precipitation and the past 2 years' PDSI might not be independent, this was not the case as the correlation between these was adj-r^2 = 0.00, $P = 0.958$.

or amount of area burned by managed lightning fire *v*. periods of cautious management that correspond to different approaches by various managers. These long-term management decisions have consequences and cumulative effects that can result in future impacts (Miller *et al.* 2020).

Global warming with impacts on wildfires makes a focus on prescription burning more important than ever. As observed in this study, the duration of wildfires has increased in recent years on both NPS and USFS lands, which many would interpret as evidence of global warming impacts (e.g. Williams *et al.* 2019). In the present study, there were weak correlations between fire activity and temperature and drought. Understanding these patterns requires recognition that climate impacts both fuel moisture and fuel load, e.g. droughts may enhance fire activity in woody vegetation owing to reduced fuel moisture but decrease activity in grasslands owing to limited grass growth (Crimmins and Comrie 2004, Keeley and Syphard 2017). The effect of climate change is confounded by a long-standing increase in forest fuels due to effective fire exclusion (Keifer 1998, Steel *et al.* 2015). Parsing out the role of fuel accumulation and global warming in accounting for Sierra Nevada fires of the 21st century remains an important avenue for research.

Conclusions

NPS and adjacent USFS lands in the Sierra Nevada have had very different histories in the application of prescription burning. Despite the later commitment to annual Rx burning in these national forests, the proportion of area burned in the last decade of this study is approximately comparable between these NPS and USFS lands. However, NPS total area burned by prescription, which includes both planned Rx burns and wildfires managed for resource benefit, is substantially greater than on USFS lands, which has not capitalised on managing wildfires for resource benefit. Nonetheless, the total area burned by prescription on both NPS and USFS lands is far short of what is required to return these ecosystems to anything close to their natural fire regime. Solving this problem is not close to a solution, though a thorough evaluation of burn windows throughout the year will contribute to increasing Rx burning opportunities.

Conflicts of interest

The authors declare no conflicts of interest.

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