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A quantitative comparison of forest fires in central and northern California under early (1911–1924) and contemporary (2002–2015) fire suppression

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Abstract. Most studies of fire-regime changes in western North American forests rely on a reference period that predates Euro-American settlement. Less is known about fire-regime changes relative to the early onset of major change agents, i.e. fire suppression and timber harvesting. We digitised ledgers that contained over 18 000 individual fire records from 1911 through 1924 (early suppression period). We performed analyses comparing a subset of these fire records, largely in mixed-conifer forests, to similar records from 2002 through 2015 (contemporary period). Mapped ignition frequencies indicated similar geographic patterns for lightning-caused fires between periods, but notable shifts in certain areas for human-caused fires. There was no statistical difference in annual number of human-caused fires between the early suppression and contemporary time periods. However, there was a major shift in the distribution of burned area across fire size classes. Fires >12 145 ha accounted for 0–6% of total burned area in the early suppression period, and 53–73% in the contemporary period. Also, both the total number and percentage of fires >2024 ha occurred significantly earlier in the year in the contemporary period. These shifts are likely driven by large-scale changes in fuel loads and continuity, and possibly exacerbated by climatic warming.

Additional keywords: departure; fire exclusion; fire statistics; mixed conifer forest.

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Introduction

Prior to Euro-American settlement and Native American depopulation, fires burned through most mixed-conifer dominated forests of California approximately every 7–12 or so years (Van de Water and Safford 2011), resulting in over one million ha of forest burning in the state in an average year (Stephens *et al.* 2007; North *et al.* 2012). These fires were ignited both by Native Americans, to promote different plant species for food and fibre as well as to increase the ease of travel (Lewis and Bean 1973), and by lightning. Incidence of fire declined dramatically around the time of the mid-19th century gold rush, coinciding with a sharp drop in the Native American population (Taylor *et al.* 2016). Thus, by the time of establishment of the forest reserves (Sudworth 1900) and the shortly thereafter – the formation of US Forest Service (1905) – fire was already considerably less prevalent, at least in some forested areas, illustrating the prominent role of human ignitions in the historic fire regime (Skinner *et al.* 2009).

Early foresters noted the open condition of many forests in California, believing that the land could support far more trees if fire were kept out (Sudworth 1900; Show and Kotok 1924). Thus, a focus of early US Forest Service efforts was to suppress all fires in order to minimise fire damage to existing trees and allow for recruitment of new trees, with the intent of increasing stocking and ultimately timber yields (Show and Kotok 1923; Show and Kotok 1924). Forest lookouts began to be used between 1911 and 1913 to detect and locate fires (Show and Kotok 1923), but the work of suppression was accomplished mainly with simple hand tools by crews who reached fires by foot or on horseback. Show and Kotok (1929) noted that 'the organisation of forest-fire control on the National Forests has reached a high level of effectiveness, considering the resources available.' In addition to fire suppression, another battle was being fought to change the minds of landowners and citizens who continued pushing to use fire (i.e. 'light burning') to enhance forage and protect mature forest from destructive wildfires (Greeley 1920; White 1920; Show and Kotok 1924).

Effectiveness of early fire suppression efforts was at least in part due to forest surface fuels that were still fairly light and discontinuous, and forest density that was much lower than today (Scholl and Taylor 2010; Knapp *et al.* 2013; Collins *et al.* 2017). After a century or more of fire suppression, forest fuel loads are much greater and more continuous both horizontally and vertically (Taylor *et al.* 2014; Lydersen and Collins 2018). Climate has also changed. Warmer temperatures have led to earlier snow melt in many forested areas, increasing fuel drying and lengthening the fire season (Westerling 2016). These changes in the amount and continuity of fuels, as well as their availability for burning (dryness, fire season length) have implications not just for the intensity of fire, but how fire is fought. Increases in fire intensity have to some extent been kept in check by continued evolution of fire-fighting technology and resources.

In this paper, we used records of individual fires recorded by each of the National Forests (NFs) in California that occurred between 1911 and 1924. Show and Kotok (1923, 1929) previously summarised these fire records in ledgers to facilitate analyses for their two reports. However, the ledgers not only contained the summaries of the 10 000+ fires spanning 1911–1920 used in their two published reports, but also included fires for the remainder of the state through 1924, with 1924 appearing to be the last year that these records were collected. The total number of individual fires in the ledgers was 18 686. To our knowledge, there has been little to no use of these fire records beyond the Show and Kotok reports.

In the following, we present a set of analyses comparing these early suppression period (1911–1924) fire records to comparable records in the contemporary period. The contemporary period used was 2002 to 2015, which was chosen for two reasons: availability of comparable records and consistency of record length between the two periods. Our overall goals were to investigate potential changes in forest fire activity over time and, if change was evident, provide additional insight into drivers of this change. Our specific objectives were to compare: (1) mapped fire occurrence throughout the study area, (2) total number of fires that occurred, (3) distribution of total area burned by different fire size classes, (4) timing of fire occurrence throughout the calendar year, and (5) initial fire suppression response time. For each of these objectives we separated fires by general cause (human *v.* lightning) to identify potential drivers of change, or lack thereof, between the two time periods. We added two objectives to further explore the results from objectives 3 and 4. These additional objectives were: (6) compare seasonal timing of large fire (>2024 ha) occurrence between time periods and (7) compare climate and the relationship between climate and area burned between the two time periods.

Methods

Study area

For this study, we focused on the fire records that were within NFs containing the majority of conifer-dominated forests in northern and central California (Fig. 1). The area consists primarily of the Klamath Mountains in the north-western corner of the state and continues in a clockwise direction around northern California, including portions of the southern Cascades, Modoc Plateau and Warner Mountains, and concluding with the Sierra Nevada Mountains on the eastern side of the state.

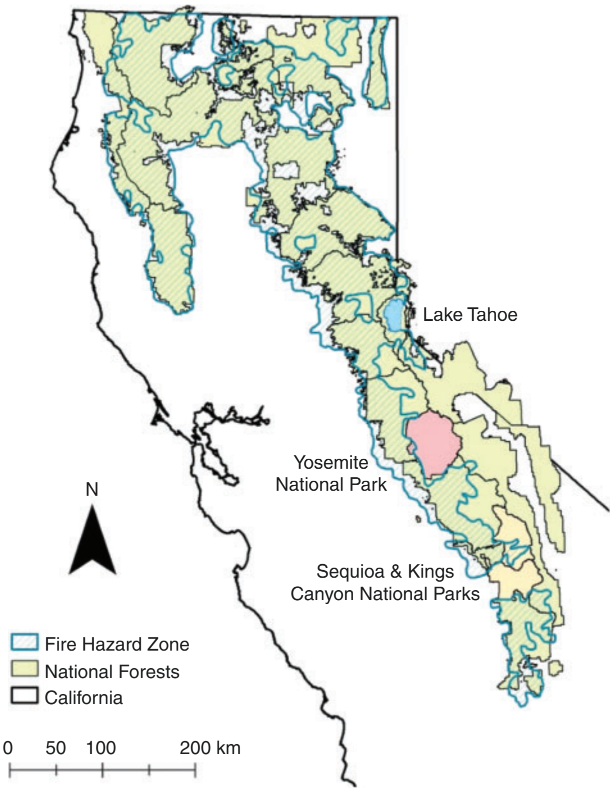

Fig. 1. Map of the study area. National Forests during contemporary period (2002–2015) clock-wise from bottom left: Mendocino, Six Rivers, Shasta–Trinity, Klamath, Modoc, Lassen, Plumas, Tahoe, Lake Tahoe Basin Management Unit, Eldorado, Humbolt–Toiyabe, Stanislaus, Inyo, Sierra, and Sequoia. Portions of Yosemite National Park and Sequoia and Kings Canyon National Parks within Show and Kotok's (1923) Fire Hazard Zone were part of the National Forests during the early period (1911–1924).

Conifer-dominated forests within the study area are geographically variable, with different dominant species and variation in structure depending upon latitude, longitude, elevation, past forest management actions and natural disturbance events. In general, however, the most common conifer species include ponderosa pine (*Pinus ponderosa*) at lower elevations; white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) at intermediate elevations (in the Sierra Nevada Douglas-fir disappears south of Yosemite National Park); and Jeffrey pine (*P. jeffreyi*) and red fir (*A. magnifica*) at the higher elevations. Although most of the dominant conifer species occur throughout the study area, overall conifer diversity is higher and forest environments are generally more mesic with correspondingly greater vegetation diversity and complexity in the Klamath Mountains (Skinner *et al.* 2018). Despite this diversity, historical fire regimes were fairly similar throughout the study area, primarily consisting of frequent, largely low- to moderate-severity fire (Skinner and Taylor 2018; Skinner *et al.* 2018; van Wagtendonk *et al.* 2018). Climate throughout the

Table 1. Fire report summary information recorded in the early suppression period ledgers

Variable	Values
Forest name	Angeles, California, Cleveland, Eldorado, Inyo, Klamath, Lassen, Modoc, Mono, Plumas, Santa Barbara, Sequoia, Shasta, Sierra, Stanislaus, Tahoe, Trinity
Fire year	1911–1924
Fire discovery month	1–12
Fire discovery day	1–31
Public Land Survey System (PLSS) meridian	Humboldt, Mount Diablo, San Bernardino, Willamette
PLSS section	1–36; Sometimes more than one section was listed.
PLSS township	Integer number
PLSS township direction	North, South
PLSS range	Integer number
PLSS range direction	East, West
Fire size	Acres
Fire size class	Class A, 0.25 acre (~0.1 ha) or less; Class B, more than 0.25 acre (~0.1 ha), but less than 10 acres (~4 ha); Class C, 10 acres (~4 ha) or more, but less than 100 acres (~40 ha); Class D, 100 acres (~40 ha) or more, but less than 300 acres (~121 ha); Class E, 300 acres (~121 ha) or more, but less than 1000 acres (~405 ha); Class F, 1000 acres (~405 ha) or more, but less than 5000 acres (~2024 ha); Class G, 5000 acres (~2024 ha) or more Note: these size classes are the same as those used in contemporary fire reports.
ON or OFF forest	Indicates whether the fire occurred either on, off, or both on and off a National Forest.
Cause	Lightning, Railroad, Incendiary, Brush burning, Campers, Smoking, Miscellaneous, Unknown
Cover type	One or more one or two letter codes for vegetation cover type(s) depending upon the source fire report form and person that filled out the form.
Cover type code	This field was hand written next to the fire cover type in the ledger. It appears that this field was derived from some unknown vegetation map. For fires off forest this field was blank or had the value of 'out' or 'off'. Numeric codes were used for 1921–1924. These numeric codes match the cover types listed in table 1 from Show and Kotok (1929). For 1911–1920, the codes were one- or two-letter codes similar to the Cover Type.
Slope	For 1920–1924, this field contains letter code values indicating: Level, Gentle, Moderate, Steep, Very Steep, MIXED). For 1914–1919, values are percentage slope.
Exposure	N, NE, E, SE, S, SW, W, NW, ALL, MIXED
Cost	Dollars and cents
Start to work	Length of time from outbreak of fire to attack on fire (hours); recorded in 1914–1924, i.e. time-to-initial-attack.
Discover to work	Length of time from discovery of fire to attack (hours); recorded in 1914–1924.

study area is Mediterranean, but broad-scale variation is influenced by elevation, latitude and proximity to the Pacific Ocean, with local variation caused by steep and complex terrain (Minnich 2007; Skinner *et al.* 2018).

Early suppression fire records

We entered all records from the ledgers into a geographical information system (GIS) database. There were two different fire-reporting forms used during the early suppression period (1911–1924), but much of the basic information was the same between both forms (Table 1; Table 1 in Show and Kotok 1923). We entered the summary information from the ledgers into an ArcInfo geodatabase using the public land survey system (PLSS) section centres provided in the ledgers as geographic coordinates. The original fire report form appears to indicate that the recorded PLSS section should be the location of where the fire started (Show and Kotok 1923), but not the individual fire perimeters. For some fires, multiple PLSS sections were recorded. In those cases, we used the section at the approximate geographic centre of all listed sections.

Some attributes of individual fire records were conspicuously inconsistent. For example, the record indicated that a fire occurred within an individual NF boundary, but the PLSS location was far removed from that NF, and the fire size was too small for any portion of the fire to have occurred on a NF. In such cases, we used the PLSS location and considered the fire as having not burned on a NF. As an added difficulty, the NF boundaries in the early suppression period (1911–1924) do not entirely match the contemporary boundaries and GIS data do not exist for the early suppression period forest boundaries. Not only have NF names changed (Fig. 1, Table 1) but some NFs have gained, lost or transferred area to other units (e.g. to the National Park Service). We were able to locate a small scale map (Ayres and Hutchinson 1927) that showed the boundaries in 1927, and papers by Show and Kotok (1923, 1929) contain a few larger scale maps. We georeferenced these maps and checked for consistency between the geographic descriptions and the PLSS locations. The NFs in our study area recorded 15 366 fires, out of which 12 603 occurred at least partially on NF lands. The remaining 2763 fires did not occur on NF lands and were

Table 2. Number of fires and area burned by cause in the study area
Fires of unknown origin are included with human-caused fires

Early suppression period (1911–1924)					Contemporary period (2002–2015)				
	Human		Lightning			Human		Lightning	
Year	Number of fires	Total area (ha)	Number of fires	Total area (ha)	Year	Number of fires	Total are (ha)	Number of fires	Total area (ha)
1911	235	8035	155	2043	2002	561	67 238	276	1359
1912	221	4752	157	260	2003	469	5232	921	9384
1913	436	12 084	608	751	2004	559	8062	536	117
1914	544	17 864	350	531	2005	378	3087	255	4017
1915	717	10 367	252	555	2006	435	20 713	678	62 555
1916	615	14 850	344	3644	2007	551	32 493	425	17 251
1917	617	65 740	736	27 899	2008	520	22 380	582	265 355
1918	269	30 967	471	48 431	2009	492	4172	476	11 297
1919	530	34 413	153	469	2010	376	1351	237	3982
1920	368	26 917	516	35 672	2011	381	4124	226	8643
1921	459	15 049	142	5197	2012	535	46 895	220	19 316
1922	417	31 904	182	836	2013	465	134 554	578	10 751
1923	365	30 564	502	2607	2014	447	69 523	435	105 767
1924	659	150 028	598	15 552	2015	422	5269	798	166 147
Total	6452	453 534	5166	144 448		6591	425 093	6643	685 939

omitted from our analyses because we could not corroborate the geographic descriptions and the PLSS locations.

Show and Kotok (1923) defined a fire-hazard zone, which they indicate shows 'the area in which fires from all causes occur on a regular basis and require action' (Show and Kotok 1923, p. 32, map 4). Show and Kotok (1923) recognised that their hazard map did not include much of the higher elevation area in the southern Sierra Nevada. They explained that the lack of inclusion was because fires in these areas, which were primarily lightning-ignited, posed limited harm because of high fuel discontinuity. A beneficial aspect of focusing on the Show and Kotok hazard zone for our analyses was that most of the differences in NF boundaries between 1927 and contemporary boundaries occurred outside their fire-hazard zone. As a result, limiting all analyses to the hazard zone effectively normalised the analysis area between the two time periods. We therefore digitised the fire hazard zone from Show and Kotok's map (Fig. 1) and limited all analyses of early suppression fires to those that occurred at least partially on NFs within the 1927 boundaries and in the fire hazard zone. The area within the fire hazard zone that falls within the contemporary boundaries of Yosemite, Sequoia and Kings Canyon National Parks were NF land during the early suppression period (Fig. 1) and therefore were included in our analyses. We further removed two records from the analyses that did not have information on either size or size class which reduced the number of fires to 11 617. Five additional records did not have data on fire size, but were retained because a size class was noted. Information on time to initial attack (i.e. start to work, Table 1) was only recorded for 5321 fires. For some fires, the time to initial attack was recorded as >24. In those cases, we used 24 h as the value.

Show and Kotok (1923) expressed concern in their reported number of fires for 1911 and 1912, suggesting that fires may have been under-reported in these years. This concern appears to have been based on the low total number of fires in these 2 years relative to other years in the early suppression period. However, when fires are separated by cause, the number of lightning-caused fires in 1911 and 1912 were not outside the range of the other years (Table 2). We therefore included 1911 and 1912 in our analyses.

Contemporary fire records

For data on all fires regardless of fire size in the contemporary period, we used the fire occurrence database originally generated to support the National Fire Program Analysis (FPA) system (Short 2017). The FPA database contains fires for the period 1992–2015 across all management units in the US. We only included fires that burned at least partially on the NFs, and in the portions of Yosemite, Sequoia and Kings Canyon National Parks that were within Show and Kotok's (1923) fire-hazard zone (Fig. 1). Additionally, we limited the contemporary study period to 2002–2015 in order to maintain a 14-year record consistent with records available for the early suppression period. The resulting number of fires for the contemporary period was 13 241.

The FPA database does not include information on time to initial attack. We therefore used fire statistics for Forest Service fires in the study area from the National Fire and Aviation Management web (FAMWEB) data warehouse (https://fam.nwcg.gov/fam-web/, accessed 9 January 2018). The fire statistics contain ignition and first-action dates and times for each fire, from which we calculated time to initial attack (i.e. the difference in time between ignition and first action). We downloaded fire statistics for 2006–2014, which yielded 6732 records for the NFs in our study area. There were several fire records where the time to initial attack was over 1000 h and the cause was debris burning that could be attributed to off-season burning of slash piles that had not been completely extinguished. We decided to eliminate all records where the cause was debris burning for the analysis of time-to-initial-attack because there was not an equivalent fire cause in the early suppression fire records.

Climate

We obtained annual temperature (mean, maximum and minimum), precipitation, and Palmer Drought Severity Index (PDSI) for each year in the early suppression and contemporary periods. Annual temperature values were computed as the average of the monthly observations (mean, maximum, minimum) for each calendar year, whereas the precipitation values were the total for each hydrologic year (Oct–Sep). These observations were obtained from the California Climate Tracker (https://wrcc.dri.edu/Climate/Tracker/CA/, accessed 17 October 2018) for the two climate regions that overlapped the majority of our study area: Sierra and North Central. We averaged the observations from these two regions. Annual PDSI values were obtained from Abatzoglou *et al.* (2017) for the two major hydrologic units that overlapped our study area: Upper Sacramento and Klamath. The boundaries for these units were similar, but not directly comparable, to those for the Sierra and North Central climate regions. Again, the annual PDSI values were averaged for the two units.

Analyses

To examine geographic patterns of fire occurrence we computed ignition frequency for a given PLSS section. This frequency was calculated as the number of fire ignitions recorded for a given section divided by the number of years in each period ($n = 14$ for both). To capture change across the two time periods we spatially computed the difference in ignition frequency between periods, which we did separately for human- and lightning-caused fires. We used *t*-tests to test for differences between early suppression and contemporary periods in mean annual numbers of fires, annual area burned, mean time to initial attack, and the five climate variables. For all fire variables, separate tests were performed for human- and lightning-caused fires. Time values for time to initial attack were $\log_{10}$ transformed to better meet Gaussian requirements. Chi-Square tests were used to test for differences between early suppression and contemporary periods in monthly distributions of all fires, and just large fires (>2024 ha), as well as for differences in area burned by fire size class. Again, separate tests were performed for human- and lightning-caused fires. For comparison of fires by size class we used the size classes as documented in both early suppression and contemporary period fire records (Table 1). However, we added a very large size class (>12 145 ha) to better delineate the much larger fires in the contemporary period. All tests were performed in SAS ver. 9.4, SAS Institute Inc. (https://www.sas.com/en_us/software/stat.html, accessed 20 March 2018) using an α of 0.05.

Results

The change in mapped fire ignition frequencies between the early suppression (1911–1924) and contemporary (2002–2015) period differed for human- and lightning-caused fires (Fig. 2). For human-caused ignitions, ignition frequencies increased by more than 0.5 fires per year in several areas. The greatest increases occurred in the Klamath Mountains, along the Trinity River (see point 1 in Fig. 2), and the central Sierra Nevada around Lake Tahoe (see point 2 in Fig. 2). Ignition frequency increases also occurred in lower elevation areas in the central and southern Sierra Nevada, but at a less pronounced rate (0.25 to 0.5 fires per year). By contrast, strong decreases in human-caused ignition frequency, relative to the early suppression period were noted in lower elevation areas in the north-central Sierra Nevada (see point 3 in Fig. 2). Moderate decreases occurred in lower elevation areas of the northern Sierra Nevada and parts of the southern Klamath Mountains (Fig. 2). Changes in lightning-caused ignition frequency were much more subtle; with the most notable change being increased ignition frequency in the high elevation areas of the southern Sierra Nevada (see point 4 in Fig. 2). Low to moderate increases occurred in the north-eastern Sierra Nevada, as well as in the northern Klamath Mountains.

Surprisingly, there was no statistical difference in annual number of human-caused fires between the early suppression and contemporary time periods ($P = 0.82$). This is evident in the similar mean and median values across the two time periods (Fig. 3). Furthermore, total area burned by human-caused fires was similar for the two time periods ($P = 0.89$; Table 2). However, the year-to-year variability in number of human-caused fires, as indicated by the box plots, was noticeably larger for the early suppression period (Fig. 3). High year-to-year variability in the annual number of lightning-caused fires occurred in both time periods (Fig. 3). This variability likely contributed to the lack of statistical difference in the two distributions ($P = 0.20$), despite noticeable differences in the mean and median values between the two periods. The total area burned by lightning-caused fires was much greater in contemporary period than in the early suppression period (Table 2), but again due to the high degree of variability, the difference in annual area burned was not statistically significant ($P = 0.09$).

The distribution of total area burned across fire size classes differed between the early suppression and contemporary time periods (Fig. 4). This difference was statistically significant for both human- and lightning-caused fires ($P < 0.01$). In the early suppression period very large fires (>12 145 ha) human- and lightning-caused fires accounted for 6 and 0% of total burned area respectively (Fig. 4). By contrast, very large human- and lightning-caused fires accounted for 73 and 53% of total burned area in the contemporary period respectively (Fig. 4). Conversely, small fires (≤121 ha) made up ~10% of the total burned area in the early suppression period (for each cause), but only 1–2% in the contemporary period.

For both human- and lightning-caused fires, monthly distributions of fire occurrence were significantly different between the early suppression and contemporary periods ($P < 0.01$ for both tests). These differences were generally characterised by a shift towards increased fire occurrence earlier in the calendar year for the contemporary period (Fig. 5). Additionally, for human-caused fires in the contemporary period there was a noticeable expansion of the overall distribution across all months. This expansion was less apparent for lightning-caused fires, which mainly occurred May–Oct in both time periods (Fig. 5). A very small number of lightning-caused fires occurred earlier (April) and later (November) in the contemporary period.

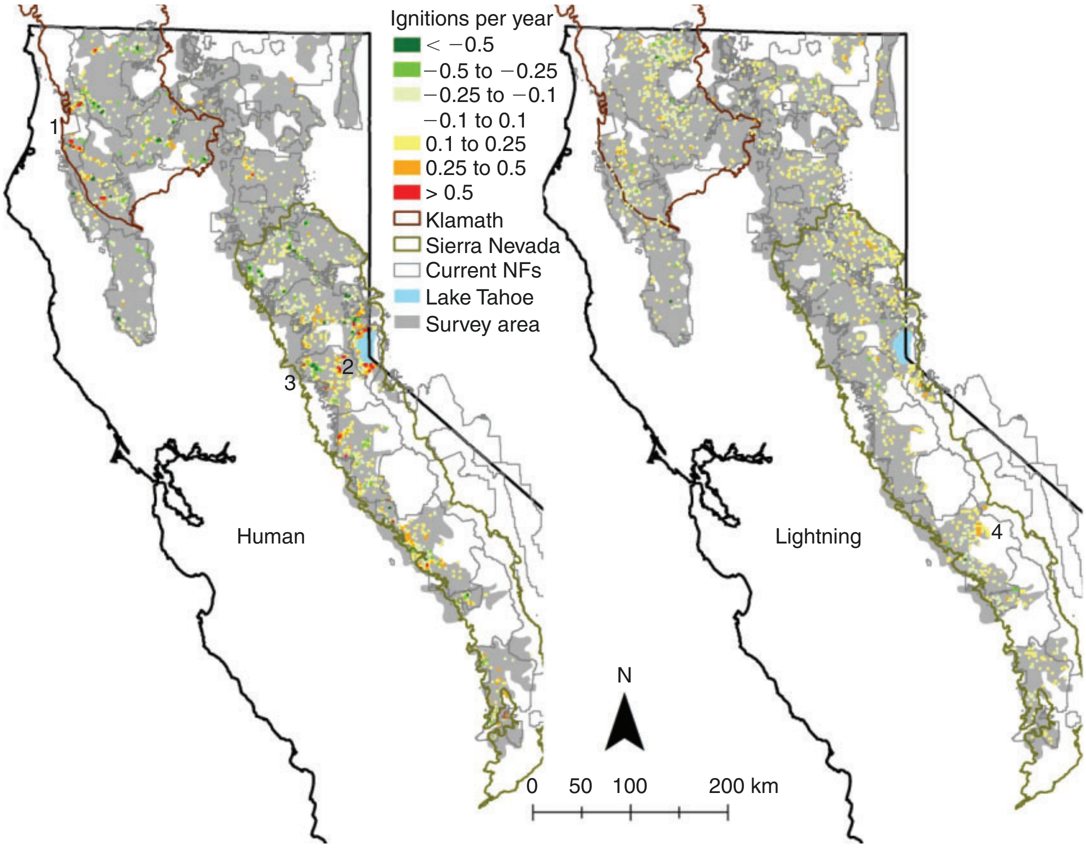

Fig. 2. Mapped change in fire ignition frequency between early suppression and contemporary periods, separated by fire cause. Positive changes (orange and red) indicate more ignitions in the contemporary period, whereas negative change (green) indicate fewer ignitions, relative to the early suppression period. Numbers correspond with specific areas noted in the Results section. Sierra Nevada and Klamath bioregions are identified, along with current National Forest (NF) boundaries.

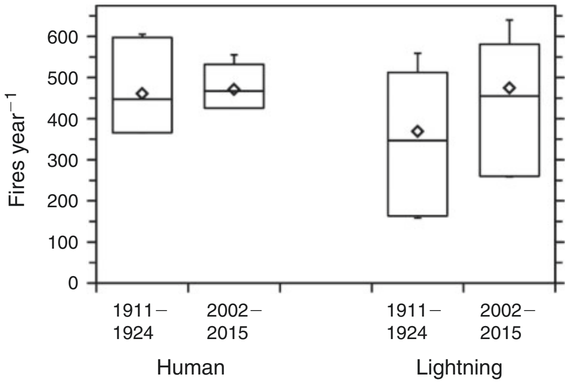

Fig. 3. Box-and-whisker plots for annual number of fires in the early suppression (1911–1924) and contemporary (2002–2015) period, separated by fire cause. The hollow diamonds represent annual means.

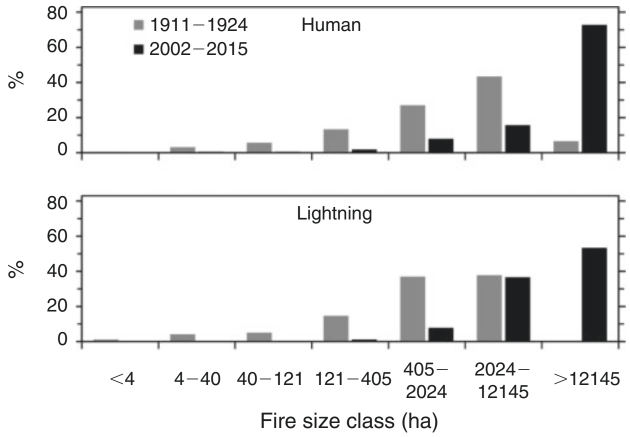

Fig. 4. Percentage of total area burned by fire size class in the early suppression (1911–1924) and contemporary (2002–2015) period, separated by fire cause.

Large fires (>2024 ha) tended to occur earlier in the year in the contemporary period ($P < 0.01$, Fig. 6). However, when broken down by cause, the average start date of large fires did not change significantly between periods (Julian date, lightning = 197.6 and 195.0, human = 229.4 and 217.1, for early suppression and contemporary periods respectively). Instead, the shift to earlier timing of all large fires appeared to be due to a shift in the main causal agent over time. Large fires were more likely human-caused (52 human *v.* 14 lightning) in the early suppression period and lightning-caused (22 human *v.*

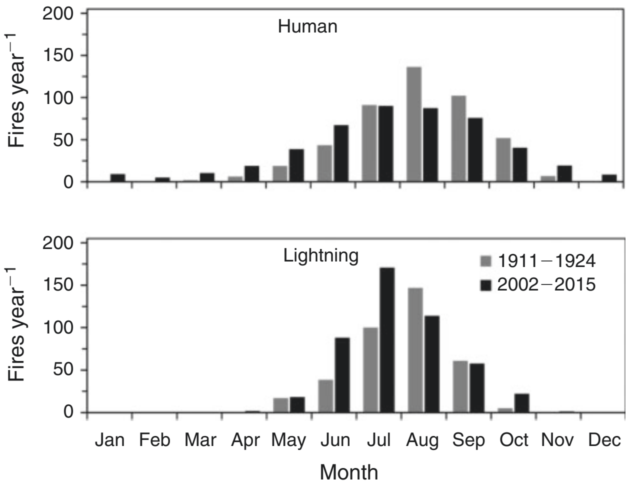

Fig. 5. Average number of fires per year by month in the early suppression (1911–1924) and contemporary (2002–2015) period, separated by fire cause.

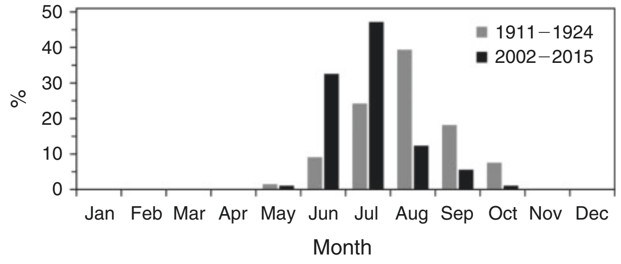

Fig. 6. Percentage of total recorded large (>2024 ha) fires by month in the early suppression (1911–1924) and contemporary (2002–2015) periods.

67 lightning) in the contemporary period, and large lightning-caused fires occurred substantially earlier than large human-caused fires in both time periods (an average of 32 days earlier for 1911–1924 ($P < 0.01$), and 22 days earlier for 2002–2015 period ($P = 0.01$)). Note, there were not enough observations in the early suppression period to conduct these comparisons using only the very large fire category (>12 145 ha).

When averaged across each 14-year period, the percentage of human- and lightning-caused fires that became large (>2024) mirrored the shift in large fire cause, with 0.74% of human-caused fires becoming large in the early suppression period *v.* 0.33% in the contemporary period, and 0.23% of lightning-ignited fires becoming large in the early suppression period *v.* 0.89% in the contemporary period. However, due to high inter-annual variability, the average difference between time periods was not statistically significant for either human- for lightning-ignited fires ($P = 0.11$ and $P = 0.09$ respectively). When moderately large fires (405–2024 ha) were included, the percentage of human-caused fires >405 ha declined significantly over time (3.08% in the early suppression period *v.* 0.87% in the contemporary period, $P < 0.01$), whereas the percentage of lightning-caused fires exceeding the moderately large threshold did not change (1.01% in the early suppression period *v.* 1.56% in the contemporary period, $P = 0.46$).

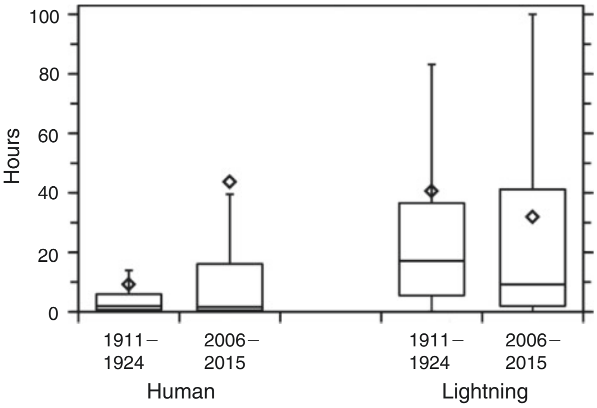

Fig. 7. Box-and-whisker plots for the amount time (in hours) taken for initial fire suppression efforts to begin on individual fires in the early suppression (1911–1924) and contemporary (2002–2015) period, separated by fire cause. The hollow diamonds represent means.

The change in time to initial attack between time periods was not consistent for human- and lightning-caused fires. For human-caused fires, median times decreased slightly from the early suppression to the contemporary time period (2.0 to 1.6 h), but both the mean and variability increased considerably (Fig. 7). This was supported by statistically significant difference between the two distributions ($P < 0.01$). Time to initial attack for lightning-caused fires was quite variable in both time periods, but both mean and median values decreased from the early suppression to contemporary periods ($P < 0.01$).

Changes in the fire regime over time coincided with climatic differences. Mean, maximum and minimum temperatures were significantly higher in the contemporary period (Table 3). The increase in minimum temperature (+2°C) was greater than that for either maximum (+0.9°C) or mean temperature (+1.5°C). Annual precipitation was unchanged between the early suppression and contemporary periods, with nearly identical means for both periods. Mean PDSI was lower (more negative) in the contemporary period, but there was enough year-to-year variability to render this difference non-significant. Plots of annual burned area *v.* annual PDSI revealed a negative and somewhat log-linear relationship for the early suppression period, although this was more evident for human-caused than lightning-caused fires (Fig. 8). This relationship was less apparent for both causes in the contemporary period. Results of simple linear regressions of log burned area and PDSI support these graphical observations with adjusted R^2 coefficients of 0.64 and 0.33 for human- and lightning-caused fires in the early suppression period and 0.22 and −0.05 for human- and lightning-caused fires in the contemporary period. Simple linear regressions of mean, maximum and minimum temperatures and precipitation with burned area showed the same trend, with higher R^2 values in the early suppression period, although the values were lower than that for PDSI.

Discussion

Our comparison of unique early suppression fire records with a similar contemporary dataset yielded several intriguing, and somewhat unexpected findings. Given the more than 10-fold

Table 3. Annual climate variables averaged for early and contemporary fire suppression periods

P-values are from individual paired *t*-tests. Abbreviations: *T*, temperature (°C); Precip, precipitation (cm); and PDSI, Palmer Drought Severity Index

Variable	1911–24	2002–15	*P*-value
Mean *T*	9.9	11.4	<0.01
Maximum *T*	17.1	18.0	<0.01
Minimum *T*	2.8	4.8	<0.01
Precip	107.3	107.7	0.97
PDSI	−0.3	−0.9	0.33

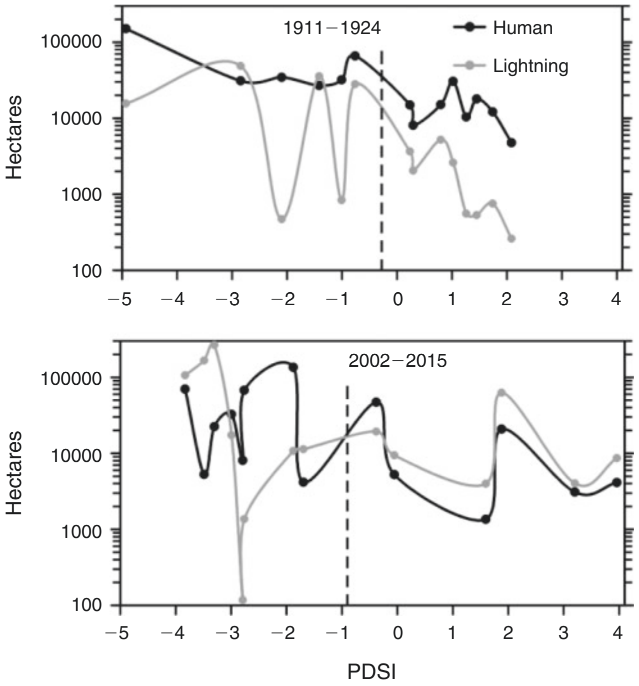

Fig. 8. Relationship between annual area burned and average annual Palmer Drought Severity Index (PDSI) in the early suppression (1911–1924) and contemporary (2002–2015) period, separated by fire cause. Note the log scale on the vertical axis.

increase in the human population of California between 1920 and 2010 (3.43 million in 1920, 37.25 million in 2010 – US Census, https://www.census.gov/data/tables/2010/dec/pop-change-data-text.html, accessed 12 June 2018), a considerable increase in both human-caused fires and area burned in those fires might have been expected, so the similarity in annual number of human-caused fires and total area burned between the two time periods was surprising (Fig. 3, Table 2). In particular, expansion of human communities adjacent to large tracts of forestland, as well as increased use of both major transportation corridors and recreation sites within forests would all lead towards greater potential for human-caused forest fires. It is possible that human activities in forests during the early suppression period (e.g. timber operations, grazing, mining and the dispersed camping associated with those activities) may have been more likely to start a fire. In addition, greater prevention efforts in the contemporary period (e.g. fire danger rating and related restrictions, Smokey Bear ad campaign) likely played a role in reducing the number of human-caused fires per person. The influence of human activity on fire in the early suppression period was evident in the north-central Sierra Nevada, where ignition frequency was considerably greater in the early suppression period (see point 3 in Fig. 2). This area had a long history of mining and particularly heavy timber activity in the early 1900s (Stephens and Collins 2004). The intentional use of fire in the early suppression period through 'light burning' is another contributing factor. This could explain the moderate reductions in human-caused ignition frequency in the southern Klamath Mountains and northern Sierra Nevada from the early period to the contemporary period (Fig. 2). According to Show and Kotok (1923), these areas were a hotbed for 'incendiarism' during the early suppression period, where many grazers and timberland owners continued to practice 'light burning' to improve forage and reduce accumulated surface fuels.

The increase in the proportion of total area burned by very large fires (>12 145 ha or 30 000 acres) in the contemporary period (Fig. 5) was not unexpected; however, the magnitude of this change was surprising. The largest fire in the study area during the early suppression period was 15 131 ha (37 374 acres), and this and one other fire were the only fires that exceeded 30 000 acres. By contrast 25 fires exceeded 30 000 acres in the contemporary period, the largest of which was 103 586 ha (255 858 acres). Inasmuch as fire size is a product of fire growth and fire containment, comparing the two periods likely reflects changes both in how fires burned (mostly fuel conditions and weather variables) and how they were put out (a function of people and tools used to contain fires). Thus, one of the likely factors contributing to this change in the fire size distribution is the efficiency of contemporary fire suppression efforts. Most fires burning under less than extreme conditions are contained at small sizes, which effectively ensures that the only fires that 'escape' initial suppression efforts are those that burn under extreme conditions (Finney *et al.* 2011; North *et al.* 2015). As a result, the fires that tend to account for a majority of the area burned are those that spread rapidly, and ultimately become very large. What is particularly interesting about this comparison of area burned by fire size class is that there was arguably aggressive fire suppression in the early suppression period, yet area burned was more broadly distributed across size classes. One explanation is that, although fires undoubtedly escaped initial fire suppression efforts, forests in the early suppression period lacked the widespread fuel continuity present in the contemporary period (Lydersen and Collins 2018).

Climate could be another factor contributing to the observed differences in area burned by very large fires. In particular, an uptick in extreme fire weather events, which has been associated with large fires within the study area during the contemporary period (e.g. Lydersen *et al.* 2017), could be partially responsible. Although sufficient temporal or spatial resolution in weather data does not exist to formally compare fire weather between the two periods, extreme fire weather has been occurring more frequently throughout the northern Sierra Nevada since the mid-1990s (Collins 2014). These increases, combined with significantly higher annual temperatures in the contemporary period

(Table 3) indicate the potential for differences in fire weather patterns between the two periods. However, neither PDSI nor annual precipitation differed significantly between the two time periods (Table 3). Additionally, the relationship between annual PDSI and burned area became noticeably decoupled in contemporary period (Fig. 8). Taken together, these findings suggest that, while drying associated with climatic changes may have contributed to the increase in very large fire events, increases in fuel loading and continuity likely played an even more important role.

Large fires (>2024 ha or 5000 acres) were predominantly human-caused during the early suppression period (lightning: human = 1 : 3.7), but predominantly lightning-caused in the contemporary period (lightning: human = 3 : 1). A similar shift in the causal agent of larger fires has been reported over a shorter time period but more broadly across the western US by Westerling (2016). Among reasons for this shift in our northern and central California dataset is a relative decrease over time in number of human ignitions from August through October (Fig. 5) – often the driest time of the year when rates of spread are expected to be the greatest. The continued use of 'light burning' by private land owners, grazers and tribes during the early suppression period may have contributed to this, particularly because such burning tended to occur in late summer to early fall. Show and Kotok (1923) mention how as many as 46 'incendiary' fires were ignited on the same day in 1915 on what was then the Trinity NF.

Whereas modernisation of fire-suppression infrastructure over time reduced the proportion of human-caused fires that became large, suppression effectiveness has remained the same or even declined for lightning-ignited fires. One reason for this may be changes in the fuel complex. It is striking that the percentage of lightning-caused fires becoming large was so low during the early suppression period (0.23%), despite challenges posed by remote ignitions and limited resources available to suppress them. The comparatively low fuel loads and overall low fuel continuity in the early suppression period (Taylor *et al.* 2014; Lydersen and Collins 2018) likely limited the potential for large fires. By contrast, the much denser, more receptive and more continuous fuels in the contemporary period likely allowed for higher fire intensities and faster spread rates, even under higher moisture conditions associated with most lightning-caused fires, thus compensating for or overriding major advances in suppression capabilities. The increase in percentage of lightning-caused fires that became large in the contemporary period (0.89%), as well as the increase in proportion of large fires that are lightning-caused may also be due to fire management decisions – particularly for lightning-caused fire in more remote settings. These decisions include both changing tactics for fighting fires, i.e. more indirect suppression (Starrs *et al.* 2018) and increased use of fire to achieve resource objectives (Meyer 2015; North *et al.* 2015).

Climate likely also had some influence on the shift in timing of large fires between the early suppression and contemporary periods. The overall warmer annual temperatures in the contemporary period (Table 3) is consistent with a trend over the last several decades towards warmer spring temperatures (Westerling 2016), which would tend to increase fire activity in the early season. This is supported by our finding that overall fire occurrence and large fire occurrence was earlier in the contemporary period (Fig. 5, 6). However, this shift in the timing of large fires also appears to be the result of change in the predominant causal agent. Large lightning-caused fires typically result from numerous simultaneous ignitions – events which tend to occur earlier in the season and not necessarily at times of lowest seasonal fuel moisture (Estes *et al.* 2012). In the contemporary period, large human-caused fires are more often single ignitions that escape initial attack because of extreme conditions, including low fuel moisture levels – which tend to occur later in the season (Miller *et al.* 2012). Modern suppression capabilities have increasingly been able to deal with a single ignition scenario, but less so the multiple simultaneous lightning ignitions. A drop off in number of large fires after July under contemporary suppression (Fig. 6), well before peak seasonal fuel dryness (Estes *et al.* 2012), suggests that fuel moisture alone is not driving large fire occurrence. In the contemporary period, the monthly distribution of large fires coincided with a peak in lightning events that resulted in >50 ignitions (E. E. Knapp, unpubl. data from this dataset). Thus, the interacting role of climate, suppression actions and suppression capability need to be factored into any analysis of mechanisms of fire regime change over time.

The increase in time-to-initial-attack for human-caused fires in the contemporary period was also quite surprising (Fig. 7). Our expectation was that the advancements in communication and transportation, along with greater numbers of dedicated fire suppression personnel, in the contemporary period would have resulted in noticeable reductions relative to the early suppression period. However, as a counter-point to this expectation, it is possible that there were more people in forests during the early suppression period that were empowered and capable of performing initial fire suppression activities. It is also possible that many of the people who caused the fires were the same people who initially acted to suppress fires.

Our results, of course, indicated more predictable changes in fire occurrence as well. First, the notable increase in the frequency of human-caused ignitions in high-use recreation areas in the contemporary period (points 1 and 2 in Fig. 2) is not surprising given the increase in human population over time. However, little to no change was evident in other high use recreation areas, so other factors not considered here were likely in play. An in-depth spatial analysis of fire occurrence is beyond the scope of this work, but would be possible with these datasets. Second, the decrease in time-to-initial attack for lightning-caused fires (Fig. 7) is likely driven by advancements in transportation (better road systems, vehicles and aircraft). Lastly, the general similarity in the geographic patterns or annual number of lightning-caused fires between the two time periods (Fig. 3, 4) was also more in line with expectations. This finding suggests that there were no dramatic changes in number of lightning events or likelihood of a lightning strike starting a fire. Although a trend towards more acres burned per year in lightning-caused fires was seen in the contemporary period, the high degree of year to year variation and only a 14-year sample limited our power to detect significant changes over time.

It is worth noting that the fire-reporting system that the early suppression records came from was originally developed to track the money spent on suppressing fires. Thus Show and

Kotok's (1923) fire-hazard zone did not track the high elevation lightning ignitions in the southern Sierra Nevada, where fire spread is limited by physical barriers and lack of fuel. As a result, our early suppression fire records are not a complete record of all fires on the NFs. Even within the mapped fire-hazard zone, not all fires may have been captured. As mentioned previously, Show and Kotok (1923) indicated that the number of fires for 1911 and 1912 may be under-reported in their data. For fires that occurred at least partially on Forest Service lands in 1911, the Show and Kotok fire-record data indicate that 550 fires burned 27 227 ha on all NFs in California. An independent accounting of fires in 1911 by Plummer (1912) reported 797 fires burned 26 916 ha, which seems to support Show and Kotok's assertion at least in number of fires. If we include all fires in the Show and Kotok ledgers, regardless of whether the fire occurred on Forest Service land or not, there were still fewer fires ($n = 699$), but those fires burned a larger area (40 956 ha). We do not know the source of the discrepancy between the fires reported in the ledgers and the summary data reported by Plummer (1912), but if the number of fires were under-reported, the comparison with area burned data suggests the under-reported fires were mostly small and likely <0.1 ha.

In the contemporary period, the fire-reporting system was still primarily a tracking system for costs, but it has become a more complete record of ignitions due to the advancement in firefighting capabilities that allow for response to all fires, even in remote locations, and no matter how small. To test whether completeness of the fire record, particularly for the smallest fires, might have influenced our comparisons over time, we reran the Chi-Square tests on distribution of burned area by size class without the fires in the smallest size class (<0.1 ha). The distributions for both human- and lightning-caused fires remained significantly different between times ($P < 0.01$). Although the somewhat higher (but not statistically significant) number of lightning-caused fires in the contemporary period could stem from underreporting in the early suppression period, it is not clear that this is the case. There is some evidence of an increase in lightning over the last century due to climate change (Romps *et al.* 2014; Westerling 2016). Increased fuel loads and continuity may have also resulted in a higher proportion of lightning strikes starting fires. Even if small fires (<0.1 ha) were underreported in the early suppression period, this does not affect the overall conclusion regarding the significant increase in area burned in the largest fire size class (>12 145 ha) over the last century (Fig. 4).

Despite these limitations, these comparisons offer new insight into the potential drivers of change in fire occurrence and effects. One noteworthy example of this is the similarity in annual human-caused fires between the two time periods. Whereas several of largest and most problematic recent fires in Sierra Nevada, at least with respect to proportions and spatial patterns of stand-replacing effects, have been human-caused (Stevens *et al.* 2017; e.g. 2007 Moonlight Fire, 2013 Rim Fire, 2014 King Fire), similarity in numbers of annual human-caused fires and the fact that timing of human-caused fires has shifted towards earlier, rather than later in fire seasons when fuels would presumably be at their driest state (Estes *et al.* 2012), suggests that human influence on ignitions may not explain the departure in contemporary fire patterns. It is much more likely that increased fuel continuity and overall fuel loads, a climate more conducive for fire spread (Parks *et al.* 2018), and changes in fire suppression tactics and effectiveness are interacting to explain the observed differences between early suppression and contemporary fire patterns.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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