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The outsized role of California's largest wildfires in changing forest burn patterns and coarsening ecosystem scale

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ABSTRACT

Although recent large wildfires in California forests are well publicized in media and scientific literature, their cumulative effects on forest structure and implications for forest resilience remain poorly understood. In this study, we evaluated spatial patterns of burn severity for 18 exceptionally large fires and compared their cumulative impacts to the hundreds of smaller fires that have burned across California forests in recent decades. We used a burn severity atlas for over 1,800 fires that burned in predominantly conifer forests between 1985 and 2020 and calculated landscape metrics to evaluate spatiotemporal patterns of unburned refugia, low-moderate-severity, and high-severity post-fire effects. Total annual area burned, mean annual fire size, and total annual core area burned at high severity all significantly increased across the study period. Exceptionally large fires (i.e., the top 1% by size) were responsible for 58% and 42% of the cumulative area burned at high and low-moderate severities, respectively, across the study period. With their larger patch sizes, our results suggest that exceptionally large fires coarsen the landscape pattern of California's forests, reducing their fine-scale heterogeneity which supports much of their biodiversity as well as wildfire and climate resilience. Thus far, most modern post-fire management has focused on restoring forest cover and minimizing ecotype conversion in large, high-severity patches. These large fires, however, have also provided extensive areas of low-moderate severity burns where managers could leverage the wildfire's initial "treatment" with follow-up fuel reduction treatments to help restore finer-scale forest heterogeneity and fire resilience.

1. Introduction

Under historical fire regimes, California's northern and Sierra Nevada low- to mid-elevation forests typically experienced regular fires (less than 25-year return interval) with a range of ecological effects (Safford & Stevens, 2017; Stephens et al., 2007). These typically frequent, low- to moderate-intensity fires shaped complex, fine-grained patterns of burn severity patches and forest structure, which conferred greater resilience – or the ability to adapt, reorganize, and maintain basic ecosystem structure and function (Walker et al., 2004) – to disturbances such as subsequent wildfire and drought (Hessburg et al., 2019; Kane et al., 2019; Stephens et al., 2018). Following Euro-American colonization and over a century of fire exclusion, changes in land use patterns have led to profound shifts in forest structure and fire regimes throughout fire-prone forest ecosystems of western North America (Hagmann et al., 2021). Coupled with a changing climate and more frequent days of extreme fire weather, increased availability of fuels has led to a well-documented increase in total annual area burned across the western United States in the last four decades (Abatzoglou & Williams, 2016; Dennison et al., 2014; Holden et al., 2018; Jain et al., 2022; Safford et al., 2022, Westerling, 2016).

While large wildfires are not unknown historically in California, the rate and scale of recent large fire events is novel (Keeley & Syphard, 2021; Safford et al., 2022). In the last several years, wildfires have rapidly increased in both size and occurrence across the state. Fourteen of the state's top 20 largest recorded wildfires occurred in the last decade; nine of which occurred in the last two years (CalFire, 2022). Many of these recent large fires have burned through fuel-laden forests under extremely dry, wind-driven conditions, resulting in major community impacts and property losses (Rosenthal et al., 2021), hazardous smoke impacts (Enayati Ahangar et al., 2022), and severe fire impacts to forests over large swaths of land (Safford et al., 2022; Stephens et al.,

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2022). Compounded by the effects of severe drought, these fires have contributed to the erosion of mature conifer forest cover in areas such as the southern Sierra Nevada (Steel et al., 2022b). These exceptionally large fires are often at the center of public and scientific narratives about the impacts of wildfires on California forests, with a dominant focus on areas of forest that experience complete or near-complete tree mortality, termed "stand-replacing fire" (Levine et al., 2022; Miller et al., 2012; Stevens et al., 2017). Recent large fires across the state have been characterized by the unprecedented size of their stand-replacing area, falling far outside the historical range of variation in these forests (Steel et al., 2018; Stephens et al., 2022). The size and spatial patterns of these stand-replacing patches have important implications for post-fire tree regeneration and successional pathways, carbon storage, and other ecosystem services and functions (North & Hurteau, 2011; Stevens et al., 2017). These trends are consistent with broader patterns identified across western North American forests, where studies from other regions have suggested increases to fire size and stand-replacing area (Cansler & McKenzie, 2014; Harvey et al., 2016; Reilly et al., 2017).

While insights into patterns and trends of stand-replacing fire are critical to understand threats to forest resilience, emphasis on stand-replacing fire alone may overshadow more complex landscape patterns shaped by large fires. Although recent studies have found that public perceptions of wildfire are changing (Miller et al., 2020; Toman et al., 2014; Weill et al., 2020), popular media descriptions of unplanned large fires tend to rely on single narratives of the disaster and destruction caused by these events (Keane et al., 2008; McCaffrey et al., 2020). While these large wildfires often have catastrophic impacts on humans and undesirable impacts on ecosystems within large high-severity patches, disentangling their more moderate effects is critical to inform land management strategies. Even with recent wildfire trends, many California forests remain in a fire deficit, and a vast increase to the pace and scale of current treatments is needed to restore forest resilience (North et al., 2021). As fire activity is projected to increase under longer and drier fire seasons caused by a warming climate (Abatzoglou et al., 2021), understanding the full range of post-fire ecological effects can inform adaptive management of large, fire-impacted landscapes.

Despite the attention it receives, total area burned is generally a poor predictor of post-fire forest conditions (Birch et al., 2014). Within an individual fire perimeter, a range of fire-caused ecological effects – hereafter, fire severity – may be present at different proportions and configurations across the landscape. At one end of the spectrum, the size and shape of stand-replacing (high-severity) patches have important implications for the capacity of forests to regenerate following fire (Stevens et al., 2017; Stevens-Rumann & Morgan, 2019). At the other, unburned or minimally burned areas of forest serve as refuge for wildlife habitat (Robinson et al., 2013), act as seed sources for regeneration in nearby stand-replacing patches (Coop et al., 2019; Schwilk & Keeley, 2006), and contribute to the overall forest structural heterogeneity across the post-fire landscape (Kolden et al., 2017; Meddens et al., 2018). Between these two extremes, a wide range of low to moderate severity fire effects – from patchy consumption of forest floor fuels to up to 75 percent tree mortality – may be present. Low- to moderate-severity fire effects can shape forest structure by reducing tree density and fuel loads, bolstering forest resilience to future disturbances (Hessburg et al., 2015; Jeronimo et al., 2019; Kane et al., 2014, 2019; North et al., 2021, 2022), biotic mortality agents (Hood et al., 2015), and drought (van Mantgem et al., 2016, 2021). More than total fire size, mosaics of these fire effects govern the post-fire forest environment and subsequent fire events (Coppoletta et al., 2016; McKenzie et al., 2011; Peterson, 2002).

In this paper, we examine the landscape patterns of large wildfires across California forests. A central question guided this study: *what is the cumulative impact of exceptionally large wildfires in terms of their area burned at different severities, and how does the impact of large fires differ from the hundreds of smaller fires that have burned across California forests in recent decades?* We address this question using a dataset of over 1,800 fires that have burned across California forests between 1985 and 2020. We begin by providing a definition for exceptionally large fires within our dataset and contextualize their emergence over the last four decades in California forests. We evaluate their cumulative impacts using landscape metrics to calculate their area burned, interior (core) area burned, and mean patch sizes across the gradient of unburned, low-moderate, and high-severity effects. We compare these impacts to smaller fires and discuss the role of exceptionally large wildfires in reshaping California forests. We consider cumulative impacts in both spatial and temporal dimensions and focus the interpretation of our findings on potential impacts to forest resilience. Specifically, we analyze the impacts of exceptionally large wildfires through the following objectives:

1. Analyze temporal trends in wildfire size and annual area burned across the study area.
2. Compare spatial patterns of exceptionally large fires to other fires, in terms of cumulative area burned and spatial configurations by severity class.
3. Assess temporal trends in high-severity fire effects and unburned refugia, and evaluate the role of exceptionally large wildfires in these trends.

2. Methods

2.1. Study area

We evaluated fires that burned predominantly in conifer forests of the Klamath, Cascades, and Sierra Nevada ecoregions in California between 1985 and 2020 (Fig. 1). Combined, these regions contain over 7.3 million hectares of conifer forest and account for more than 70 percent of the state's total conifer forest cover. Our study area is dominated by yellow pine and mixed-conifer forests with variable assemblages of ponderosa pine *(Pinus ponderosa)*, Jeffrey pine *(P. jeffreyi)*, sugar pine *(P. lambertiana),* Douglas-fir *(Pseudotsuga menziesii* var. *menziesii)*, white fir *(Abies concolor)*, incense cedar *(Calocedrus decurrens)*, and black oak *(Quercus kelloggii)* at low- to mid-elevations. In higher elevations, our study area supports upper montane forests with diverse assemblages of red fir *(Abies magnifica),* western white pine *(P. monticola)*, and lodgepole pine *(P. contorta)*. Prior to Euro-American colonization, these forests, which comprise the majority of the area burned by wildfire, supported a predominately low- to moderate- severity fire regime through a combination of frequent natural ignitions and Indigenous burning (Anderson & Moratto, 1996; Meyer & North, 2019; Safford & Stevens, 2017). Over the last century, full suppression has been the primary management response across much of the region, with a smaller subset of areas (such as Yosemite National Park) permitting the use of managed wildfire to allow naturally-ignited fires to burn (Keeley et al., 2021; van Wagtendonk, 2007).

2.2. Fire perimeters and severity data

We used a geospatial dataset of historical fire perimeters maintained by the California Department of Forest and Fire Protection (CAL FIRE) Fire and Resource Assessment Program (FRAP) to identify fires that burned between 1985 and 2020 within the study area. The FRAP dataset represents a comprehensive catalog of wildfire history across multiple land ownerships and is considered the best-available data for California. To identify fires that burned predominantly in conifer forests, we selected full fire perimeters where the following criteria were met: 1) the centroid of the fire perimeter was located in the Klamath, Cascades, or Sierra Nevada ecoregions; and 2) the fire burned over at least 50 percent conifer forest according to the LANDFIRE Biophysical Settings potential vegetation dataset (Rollins & Frame, 2006). We retained perimeters only where the total fire area was at least 4 ha to ensure each burn severity image contained a sufficient number of pixels to calculate landscape metrics. A total of 1,809 fires met these criteria.

We obtained Landsat-derived (30-m resolution) burn severity images

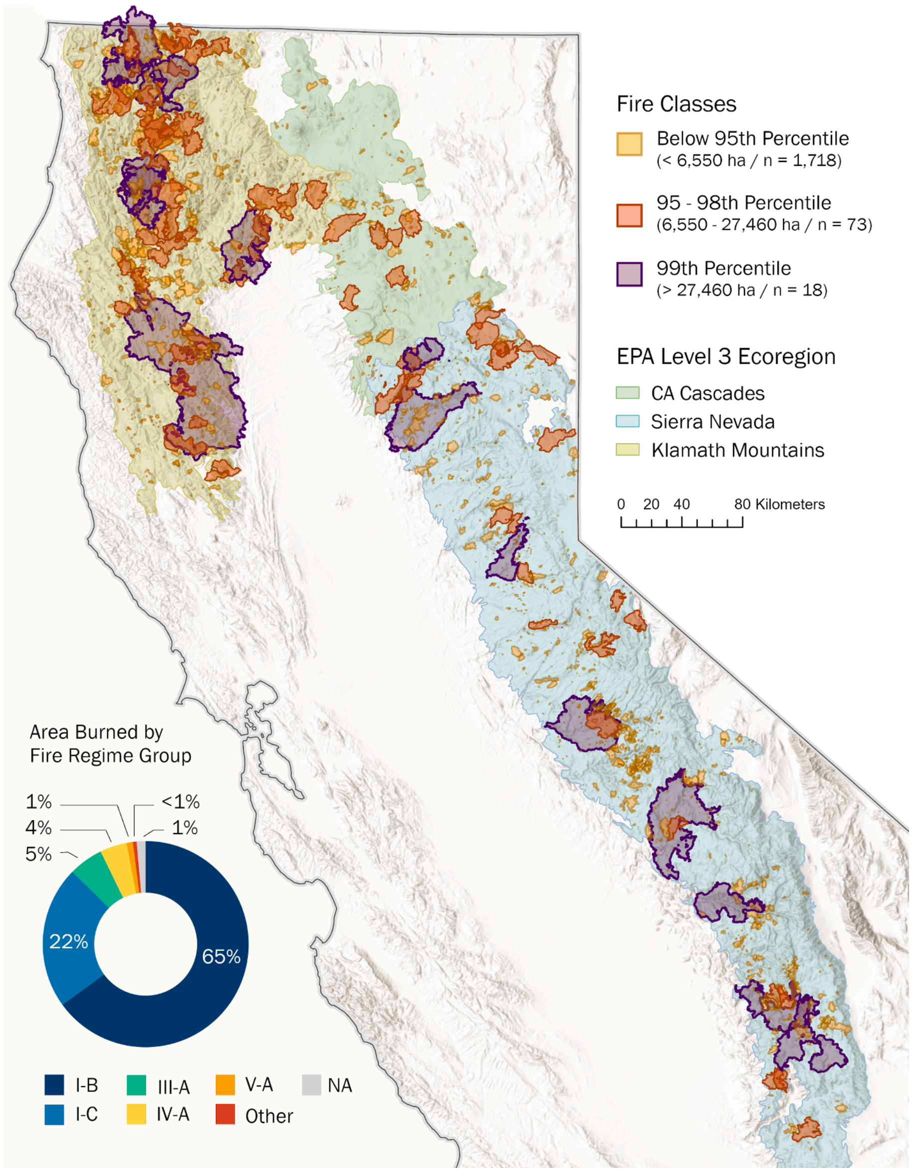

Fig. 1. Map of the study region in California, USA showing locations of 1,809 fires that burned in predominantly conifer forests between 1985 and 2020 in the Klamath (yellow-green), Cascades (green), and Sierra Nevada (blue) EPA Level III ecoregions (Omernik & Gallant, 1987). Spatial patterns of fires were analyzed by their size class: fires below the 95th percentile by size (light orange), fires between the 95th and 98th percentile by fire size (red orange), and *exceptionally large* 99th percentile fires by size (purple). The majority (87%) of area burned within our study area is concentrated in historically low-to-moderate, frequent fire regimes (LANDFIRE, 2020). Additional regime types in our study area are found primarily as dispersed pixels, mainly in riparian areas and on north-facing slopes. The graph at the bottom left shows the distribution of burned area across the study area and study period by LANDFIRE Fire Regime Groups: I-B: Percent replacement fire less than 66.7%, fire return interval 6–15 years (65% of the study area); I-C: Percent replacement fire less than 66.7%, fire return interval 16–35 years (22% of the study area); III-A: Percent replacement fire less than 80%, fire return interval 36–100 years (5% of the study area); IV-A: Percent replacement fire greater than 80%, fire return interval 36–100 years (4% of the study area); V-A: Any severity, fire return interval 201–500 years (1% of the study area). The "Other" category captures a range of fire regime types but accounts for less than 1% of the study area. An additional 1% of the study area is classified as "Not Applicable" due to sparse or no vegetation cover. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for each full fire perimeter (all pixels regardless of vegetation type) by implementing a methodology developed by Parks et al. (2019) within Google Earth Engine (GEE) (Gorelick et al., 2017). This method employs spectral indices (including Normalized Difference Vegetation Index, Mid-Infrared Bi-Spectral Index, and Relativized Burn Ratio), climatic variables, latitude, and a dataset of composite burn index (CBI) values (Key & Benson, 2006) from over 8,000 field sampling plots to produce predicted CBI values via Random Forest modeling (Breiman, 2001). We chose to use predicted CBI rather than other commonly used satellite-derived measures of burn severity (such as the Relativized delta Normalized Burn Ratio or Relativized Burn Ratio) because 1) it is a more meaningful metric of ecological change compared to unitless spectral indices, and 2) exploratory analysis showed that predicted CBI values had a closer relationship with field measurements of CBI (Picotte et al., 2019) than RBR or RdNBR. Field-based CBI measurements incorporate information about fire impacts to substrates, but the index is heavily weighted towards assessments of post-fire tree mortality and vegetation change (Miller and Thode, 2007).

We classified our continuous CBI values into three categories of fire severity for each fire: unburned-very low severity (CBI values below 0.1), low-moderate severity (CBI values 0.1–2.25) and high severity (CBI values 2.25 and above) (Miller & Thode, 2007). Although the standardized CBI breaks distinguish between low and moderate severity, previous work has also found that remotely sensed measurements of moderate severity capture a wide range of post-fire conditions and are relatively uncertain in their measurements of post-fire tree mortality and vegetation condition (Furniss et al., 2020). Because of this, we chose to combine low and moderate severity into a single class. We recognize that this single class captures a range of overstory mortality, and measurements of moderate severity in particular can be unclear in their ecological interpretations. However, we interpret our low-moderate severity class as the range of post-fire effects that reshape forests closer to resilient conditions (Collins et al., 2018; Jeronimo et al., 2019; Kane et al., 2019; Taylor et al., 2022).

2.3. Exceptionally large fires

Definitions of large fires vary widely across studies and are named somewhat arbitrarily (Gill & Allan, 2008; Linley et al., 2022; Tedim et al., 2018). Barbero et al. (2014) defined *very large fires* as greater than 5,000 ha; Keeley and Syphard (2021) described *large fires* as greater than 10,000 ha; Stavros et al. (2014) used a threshold of 50,000 acres

Table 1
Rank by size, fire name, year burned, ecoregion, total area burned, and area burned by severity class for each of the 18 exceptionally large wildfires (greater than 27,460 ha) in this study. Percentages in parentheses represent the percentage of area burned at that fire severity class as a function of the total area burned for that fire event.

Exceptionally large wildfires in California: top 1% of forest fires by size (n = 18)							
Rank	Fire Name	Year	Ecoregion	Total Area Burned (ha)	High Severity Area (ha)	Low-Moderate Severity Area (ha)	Unburned-Very Low Severity Area (ha)
1.	August Complex	2020	Klamath	419,825	190,728 (45%)	222,713 (53%)	6,384 (2%)
2.	Creek	2020	Sierra Nevada	154,672	66,077 (43%)	85,222 (55%)	3,374 (2%)
3.	Claremont-Bear	2020	Sierra Nevada	129,136	80,692 (62%)	47,437 (37%)	1,007 (1%)
4.	Rim	2013	Sierra Nevada	104,191	36,952 (36%)	62,677 (60%)	4,562 (4%)
5.	Carr	2018	Klamath	93,422	37,931 (41%)	53,550 (57%)	1,941 (2%)
6.	Castle	2020	Sierra Nevada	70,089	30,270 (43%)	38,044 (54%)	1,775 (3%)
7.	Slater	2020	Klamath	64,324	38,176 (59%)	24,161 (38%)	1,987 (3%)
8.	Rough	2015	Sierra Nevada	61,811	15,086 (24%)	40,875 (66%)	5,850 (10%)
9.	McNally	2002	Sierra Nevada	60,934	17,750 (29%)	37,231 (61%)	5,953 (10%)
10.	Red Salmon Complex	2020	Klamath	58,716	17,995 (31%)	39,920 (68%)	800 (1%)
11.	Frying Pan	2014	Klamath	54,323	17,667 (33%)	34,638 (64%)	2,018 (3%)
12.	Megram	1999	Klamath	50,935	9,247 (18%)	36,675 (72%)	5,014 (10%)
13.	King	2014	Sierra Nevada	39,947	20,854 (52%)	17,676 (44%)	1,417 (4%)
14.	Oak	2017	Klamath	37,390	12,101 (32%)	23,333 (63%)	1,956 (5%)
15.	Manter	2000	Sierra Nevada	32,257	11,391 (35%)	15,943 (49%)	4,922 (15%)
16.	Chips	2012	Sierra Nevada	31,122	9,385 (30%)	20,203 (65%)	1,534 (5%)
17.	River Complex	2015	Klamath	27,874	5,014 (18%)	20,238 (73%)	2,622 (9%)
18.	King Titus	1987	Klamath	27,688	2,993 (11%)	22,462 (81%)	2,233 (8%)

(20,234 ha) to define *very large wildfires*; Stephens et al. (2014) defined *mega-fires* as those greater than 10,000 ha. Large fire definitions are highly context dependent: they may be relative to geographic regions, vegetation types, socio-economic impacts, or individual datasets. Rather than a predefined threshold of area burned, we adopted the 99th percentile of fire sizes in our dataset (27,460 ha) to describe *exceptionally large fires* (Table 1). We focus on this top 1 percent (n = 18 fires) when discussing the cumulative impacts of exceptionally large fires on California forests. Throughout this study, we often contextualize their impacts by contrasting to those of an adjacent fire size group: fires between the 95th and 98th percentile by size, which equates to fires between 6,550 ha and 27,460 ha (n = 73 fires). Because of steep increases in area burned by large wildfires across California in recent years, we concluded that the fires in this adjacent group were not large enough to warrant the distinction of *exceptionally large*; rather, they provide a transitional space with which to evaluate the continuum of fire effects across fire sizes.

2.4. Landscape metrics

Patterns of fire severity have ecological implications at multiple scales. For example, at the individual patch scale, high-severity patch size and interior core area (the area within a patch that is at least a given distance from the patch edge) serve as a proxy for distance to live seed source and govern regeneration potential of trees (Collins et al., 2017a, 2017b; Stevens et al., 2017). At broader regional scales, the area and configuration of patches belonging to different fire severity classes influences post-fire successional dynamics and overall forest structure heterogeneity (Hessburg et al., 2016, 2019). We calculated five landscape metrics across three dimensions of spatial pattern to evaluate the cumulative impacts of exceptionally large fires: area burned by severity class, core area burned by severity class, and average patch size (Table 2). All metrics were calculated with the landscapemetrics package in R (Hesselbarth et al., 2019).

Patch level (two metrics) – We calculated area-weighted mean patch size (AREA_AM) and arithmetic mean patch size (AREA_MN) using the eight-neighbor rule for each severity class present within each fire. The former weights each patch by its proportional contribution to the total area of all patches while the latter gives equal weight to each patch (Li & Archer, 1997). Many of the largest fires in our analysis burned under a combination of wind-driven and fuel-laden conditions and may contain exceptionally large, continuous patches representing days of large fire spread. We chose to calculate both area-weighted mean and arithmetic mean patch sizes to characterize the effect of these large patches. Specifically, in fires with many small patches and a few, exceptionally large patches (right-skewed distributions), we would expect the area-weighted mean patch size to be larger, and arithmetic mean patch size to be smaller. Fires with similar area-weighted and arithmetic mean patch sizes would indicate general homogeneity of patch sizes – either many small patches or few large patches across the fire, depending on the value.

Class level (three metrics) – For each severity class within individual fires, we calculated the total area burned in hectares (class area, CA) and proportional area burned (PLAND). Class area was used to assess the cumulative impact of exceptionally large fires, and proportional area burned enables direct comparisons of patterns of fire severity across the broader population of fire sizes in our dataset.

Lastly, we calculated total core area (TCA). Core area is the area of all patches in severity class i greater than a specified distance from each patch edge. We included core area specifically as a way to evaluate potential non-serotinous conifer tree regeneration failures in the high-severity class; as a result, we defined core area by a distance threshold of 120 m (four pixels) from the patch edge, or the distance at which wind-driven seed dispersal becomes very unlikely for most mixed-conifer trees within our study area (Clark et al., 1999). We did not evaluate core area of the unburned or low-moderate severity class.

2.5. Impacts of exceptionally large fires

2.5.1. Temporal trends in area burned

We evaluated the role of exceptionally large fires in temporal trends of annual mean fire size and total annual area burned between 1985 and 2020 with a Theil-Sen (TS) slope estimator. TS slope estimators are a nonparametric technique to calculate the median overall slope across a time series from the pairwise slopes between each timestep. Previous work has established statistically significant increases in annual area burned across the study area in the last several decades (Parks & Abatzoglou, 2020, Steel et al., 2018). However, to date, there have been few studies that have evaluated the role of exceptionally large fires in recent wildfire trends. Following the critical value cutoff used in previous studies, we assessed the statistical significance of slopes using a p-value of 0.10 (Dennison et al., 2014; Holden et al., 2018; Parks & Abatzoglou, 2020). All slopes were calculated using the "trend" package in R (Pohlert, 2019).

Table 2
Description and interpretation of landscape metrics calculated for 1,809 fires that burned between 1985 and 2020 in the Klamath, Cascades, or Sierra Nevada ecoregions of California. All metrics were calculated using the landscapemetrics package in R (Hesselbarth et al., 2019). Table adapted from Singleton et al. (2021).

Metric	Acronym	Description	Interpretation of low values	Interpretation of high values	Units	Range
Class Area (Total)	CA	*Area burned:* Total area belonging to severity class *i*.	Less area burned	More area burned	Hectares	CA ≥ 0
Class Area (Proportional)	PLAND	*Percentage of landscape of class:* Measure of landscape composition. Percentage of total fire area belonging to severity class *i*.	Less proportional area burned	More proportional area burned	Percentage	0 ≤ PLAND ≤ 100
Patch Area	AREA_AM	*Area-weighted mean patch size:* Measure of patch size for each class *i*	Generally smaller patch sizes, with few or no large patches	Generally larger patch sizes, or few large patches among many smaller patches	Hectares	AREA_AM ≥ 0
Patch Area	AREA_MN	*Arithmetic mean patch size:* Measure of patch size for each class *i*	Many smaller patches, with few or no large patches	Many larger patches, or few large patches among few small patches	Hectares	AREA_MN ≥ 0
Core Area (Total)	TCA	*Total core area:* Total core area of class *i* > 120 m from patch edge. Only calculated for high-severity class.	Less interior area burned	More interior area burned	Hectares	TCA ≥ 0

2.5.2. *Spatial patterns of exceptionally large fires*

We evaluated spatial patterns of exceptionally large fires by assessing both their cumulative area burned and their individual configurations by severity class. We calculated cumulative area burned by severity class across all fires to evaluate the role of exceptionally large wildfires in shaping California forests. Previous work examining fire severity in California forests has largely focused on overall trends, with a dominant focus on high-severity effects (Mallek et al., 2013; Miller et al., 2012; Steel et al., 2018; Stevens et al., 2017). While analyses of temporal trends are invaluable to understand shifting fire regimes, we calculated cumulative totals to evaluate the overall footprint of exceptionally large fires across the landscape. We present these totals for each severity class to assess the role of exceptionally large fires in both maintaining and degrading forest resilience.

We focused on two aspects of spatial configuration to evaluate patterns and impacts of individual exceptionally large fires: proportional area burned and patch size. We performed a principal component analysis (PCA) on the proportional area burned (PLAND) of unburned-very low, low-moderate, and high-severity effects present in each fire to understand their ranges of ecological effects. We used ordination plots to visualize patterns of burn severity proportions of exceptionally large fires and directly compare those to the hundreds of smaller fires across our dataset. To understand patch-level effects of exceptionally large fires, we compared area-weighted (AREA_AM) and arithmetic (AREA_MN) mean patch sizes between exceptionally large fires and smaller fires across each severity class. We did not conduct statistical tests of significance among the means or distributions of area-weighted and arithmetic mean patch sizes between fire size groups because our dataset 1) represented the population of fires across our study area and study period and 2) contained substantial differences in sample size and variance between groups.

2.5.3. *Temporal trends in high-severity fire effects and unburned area*

We evaluated temporal trends in total annual core area burned in high-severity patches to understand the role of exceptionally large wildfires in threats to forest regeneration. We evaluated temporal trends in total area of unburned refugia within fire perimeters to evaluate potential implications for wildlife habitat, carbon storage, and seed sources left behind by exceptionally large fires. We used Theil-Sen regression to analyze the statistical significance of trend slopes.

3. Results

3.1. *Temporal trends in area burned*

The majority of exceptionally large fires in our dataset occurred in the last decade (14 of 18), with 2020 containing both the highest number and the largest fires. Between 1985 and 2020, there was a statistically significant increase in total annual area burned, with a trending (fitted) increase of 3,258 ha burned annually per the Theil-Sen model (Table 3, Fig. 2). This represents over an 1100 percent increase in annual area burned over the 35-year study period. Trends in mean annual fire size were likewise statistically significant; according to the model, mean fire size increased from 211 ha to 1,701 ha over the entire study period (47 ha annually), or an eight-fold increase from 1985 to 2020.

3.2. *Spatial patterns of exceptionally large fires*

Between 1985 and 2020, a total of 3,259,701 ha burned across the study area, of which 502,796 ha (15.4 percent) burned more than once. Within the 18 exceptionally large fires, 299,864 ha (19.8 percent) burned more than once. These 99th percentile fire sizes accounted for 47 percent of the total area burned across the study period (Table 4). The top 5 percent of fires accounted for 77 percent of the total area burned in this study.

Within all fire perimeters, 215,731 ha were unburned or burned at very low severity (Fig. 3). It is important to note that our calculations do not explicitly account for overlaps in fire perimeters, and these numbers may capture fire refugia that persist over multiple fire events. Exceptionally large fires accounted for 26 percent of this unburned refugia total; fires below the 99th percentile accounted for 74 percent of area unburned or burned at very low severity.

The majority (60.7 percent) of area burned across all fires between 1985 and 2020 burned at low-moderate severity, for a total of 1,979,773 ha (Fig. 3). This is nearly double the area burned at high severity and over 9 times the area of unburned-very low severity. The 18 exceptionally large fires accounted for 42 percent (843,000 ha) of the total area burned with low-moderate severity effects; large fires between the 95th and 98th percentile by size accounted for 32 percent of this total. Smaller fires below the 95th percentile – 1,718 fires total – accounted for just 26 percent of the area burned at low-moderate

Table 3
Results of Theil-Sen slope estimator for mean annual fire size and total annual area burned between 1985 and 2020 across the study period. Slopes indicate the estimated annual increase (positive slopes) or decrease (negative slopes) in units of hectares burned. Asterisks indicate statistically significant trends.

	Z statistic	Sen's slope (ha)	p-value	**1985 fit**	**2020 fit**
Mean Annual Fire Size*	3.50	47.26	0.00046*	211 ha	1,701 ha
Total Annual Area Burned*	3.39	3,257.88	0.00069*	10,146 ha	124,172 ha

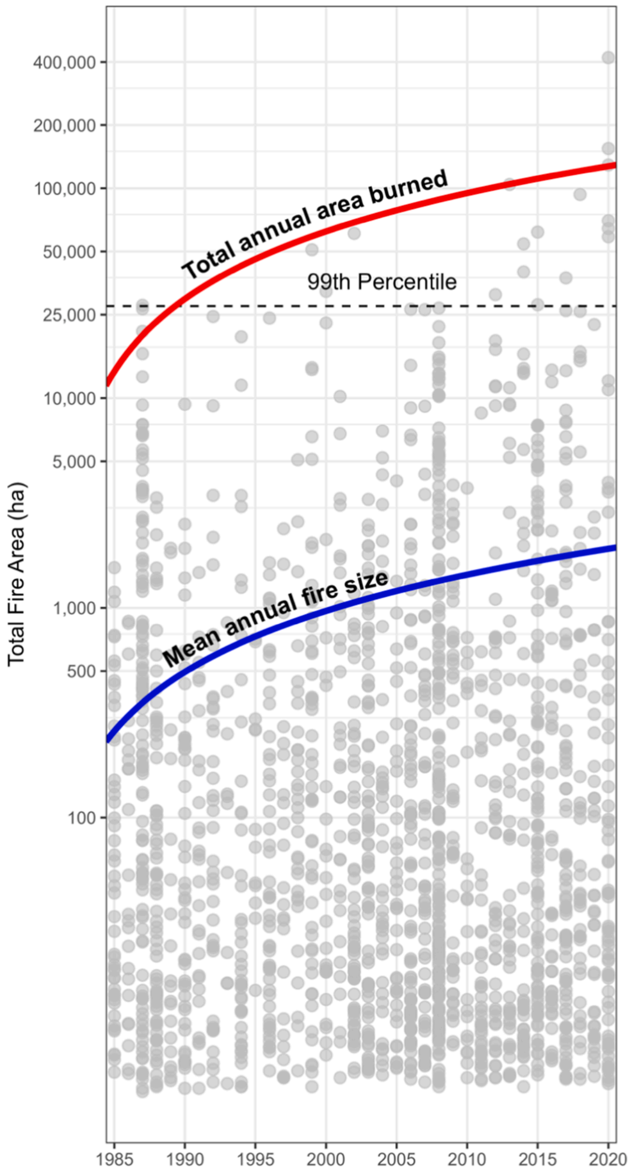

Fig. 2. Trends in mean annual fire size (blue line) and total annual area burned (red line) per Theil-Sen slope estimators. Each gray dot represents a single fire in the corresponding year. The dashed line represents the cutoff of 99th percentile of fires (exceptionally large fires) by size. Trends in mean annual fire size and total annual area burned are statistically significant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

severity.

A total of 1,065,197 ha burned with high-severity effects across the study period (Fig. 3). Exceptionally large fires accounted for the majority (58 percent) of this area with 620,307 ha burned; fires between the 95th and 98th percentiles accounted for 28 percent. The 1,718 smaller fires below the 95th percentile accounted for 148,653 ha – just 14 percent of the total high-severity area.

Principal component analysis of proportional area burned by fire severity class (PLAND) differentiated fires primarily by proportional burned and unburned area (Fig. 4). Fires with greater proportions of unburned area – entirely smaller fires – were associated with the first PC axis (61.5 percent of variation). Fires with greater proportions of low-moderate and high-severity area were associated with the second PC axis (38.5 percent of variation). All exceptionally large fires fell along the second axis, as they typically contained proportionately more high and low-moderate severity effects (Table 1). Of the 18 exceptionally large fires, 10 fires contained less than 5 percent area unburned refugia. Fifteen of 18 fires contained proportionally more low-moderate than high-severity area; fourteen of these fires were composed of over half low-moderate severity.

Area-weighted mean patch sizes (AREA_AM) varied widely between fire severity classes and fire size groups (Fig. 5). Patch sizes generally increased with fire size but increases in low-moderate and high-severity patches were much greater than unburned-very low patches. The average area-weighted patch size of unburned refugia in smaller fires was 3.9 ha; in exceptionally large fires, this increased to 44.9 ha. In the low-moderate severity class, smaller fires had average area-weighted patch sizes of 12.9 ha – orders of magnitude smaller than the average patch size of 5,077 ha in exceptionally large fires. In the high-severity class, the contrasts were also pronounced – smaller fires had an average area-weighted patch size of just 1.3 ha, while exceptionally large fires had average patch sizes of 2,301 ha.

By contrast, arithmetic mean patch sizes were more comparable between smaller and exceptionally large fires across all severity classes, but overall, exceptionally large fires contained larger mean patch sizes. Mean arithmetic patch sizes of unburned refugia were 1.1 ha in smaller fires and 1.4 ha in exceptionally large fires. Smaller fires had an arithmetic mean low-moderate-severity patch size of 3 ha; in exceptionally large fires, this mean size was 5.9 ha. In the high-severity class, mean high-severity patch size in smaller fires was 2.3 ha compared to 7.2 ha in exceptionally large fires.

3.3. Temporal trends in high-severity fire effects and unburned area

Across all fires, there was a statistically significant positive trend in total annual interior core area (TCA) burned at high severity across the study period, with a nearly 35-fold increase in area according to the Theil-Sen fitted models (Fig. 6, Table 5). Between 1985 and 2020, 378,521 ha of interior core high-severity area (i.e., greater than 120 m from the patch edge) burned. Of this, 256,912 ha (68 percent) burned in exceptionally large fires.

Model fits also indicated a statistically significant increase in unburned-very low severity area (CA) – from 2,448 ha to 6,668 ha – across the study period. In total, there were 215,731 ha of unburned-very low severity area across all fires in this study, with exceptionally large fires accounting for 55,348 ha, or 26 percent, of the total unburned-very low severity area.

Table 4
Cumulative area burned in hectares by fire size group for 1,809 fires that burned across predominately conifer forests in California between 1985 and 2020. Percentages in parentheses are summed by columns and indicate the percentage of the total area burned in that severity class (CA) across all fire size groups.

	n	High (ha)	Low-Moderate (ha)	Unburned-Very Low (ha)	Total Area (ha)
99th percentile	18	620,307 *(58%)*	843,000 *(42%)*	55,349 *(26%)*	1,517,656 *(47%)*
95-98th percentile	73	296,237 *(28%)*	628,593 *(32%)*	66,589 *(31%)*	991,419 *(30%)*
Below 95th percentile	1,718	148,653 *(14%)*	508,180 *(26%)*	93,793 *(43%)*	750,626 *(23%)*
All fires	1,809	1,065,197 *(100%)*	1,979,773 *(100%)*	215,731 *(100%)*	3,259,701 *(100%)*
Percentage of total area		*32.7%*	*60.7%*	*6.6%*	*100%*

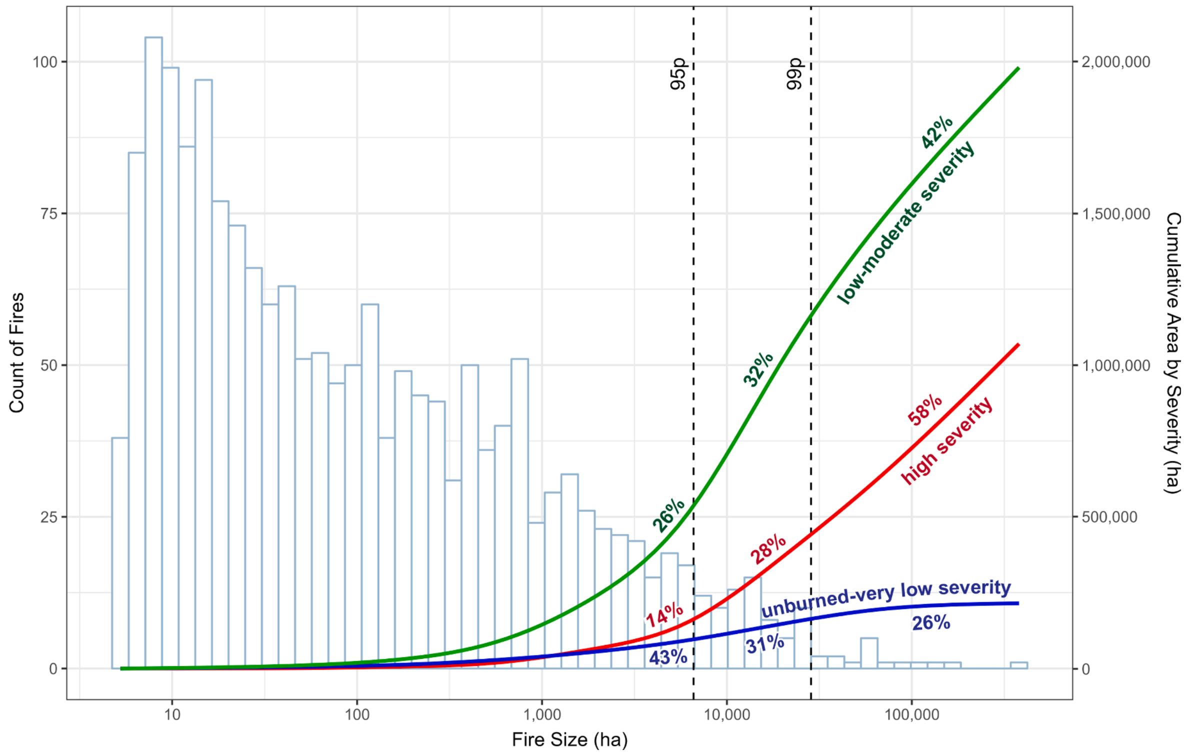

Fig. 3. Histogram of fires by size (left y-axis) for 1,809 fires that burned across conifer-dominated forests in California between 1985 and 2020. Lines represent the cumulative area burned (right y-axis) by severity class (CA), where the bottom blue line is unburned-very low severity, the middle red line is high severity, and the top green line is low-moderate severity. The dashed lines represent the 95th percentile and 99th percentile cutoffs of fires by size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

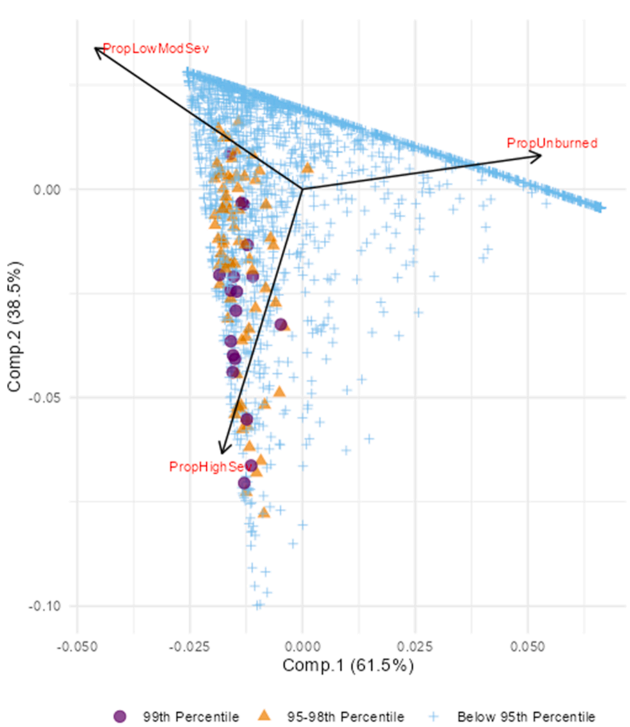

Fig. 4. Ordination of principal component analysis (PCA) of proportional area burned (PLAND) by fire severity class. Fire size groups are overlaid on the plot to show the range of spatial patterns of fire severity in exceptionally large fires (n = 18) and fires between the 95th and 98th percentiles by size. The threshold line of solid points at the top of the ordination represents smaller fires with proportionally greater area unburned.

4. Discussion

This study examined the spatial patterns and cumulative impacts of exceptionally large fires on California forests and places those impacts within the spatial and temporal context of the hundreds of smaller fires that have burned across the state from 1985 to 2020. Consistent with previous studies (Parks & Abatzoglou, 2020; Steel et al., 2018; Stevens et al., 2017), we found increasing trends in mean annual fire size, annual area burned, and the interior core area of high-severity patches, of which the latter is associated with large-scale non-serotinous conifer tree regeneration failures, persistent vegetation type conversion, diminished wildlife habitat, and loss of carbon storage (North & Hurteau, 2011; Stephens et al., 2016; Stevens-Rumann & Morgan, 2019). Across the study period, we found that the top 5 percent of fires by size were responsible for the vast majority (74 percent) of area burned with low- to moderate-severity effects, which can reduce fuel loads and tree densities, edging forests towards more resilient conditions (Hessburg et al., 2015; Jeronimo et al., 2019; Kane et al., 2019). Notably, we also found that exceptionally large fires contain much larger low-moderate and high-severity patches than smaller fires (Fig. 7), indicating a 'coarsening' of the spatial grain size between contrasting severity classes. This coarsening may erode fine-scale patterns of forest structure historically reinforced by smaller fires and the ecological processes that rely on them.

4.1. Temporal trends in area burned

We observed clear trends in increasing total annual area burned and mean annual fire size over the last four decades. Exceptionally large fires drove these trends – the majority of the top 1 percent of fires by size (14 of 18 fires) burned within the last decade, and the top 3 largest fires in our analysis burned in 2020, the final year of the study period. Previous studies have linked broad trends in annual area burned to severe

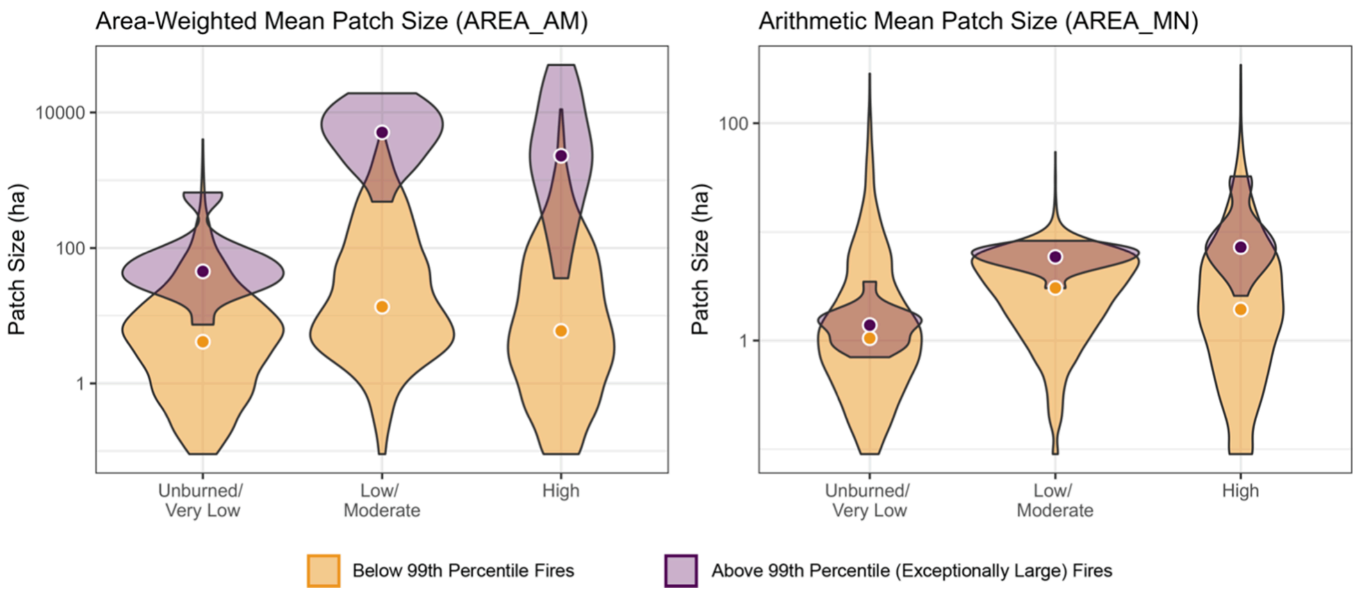

Fig. 5. Distributions of area-weighted mean patch size (AREA_AM, left) and arithmetic mean patch size (AREA_MN, right) by fire for unburned-very low, low-moderate, and high-severity classes as a function of fire size.

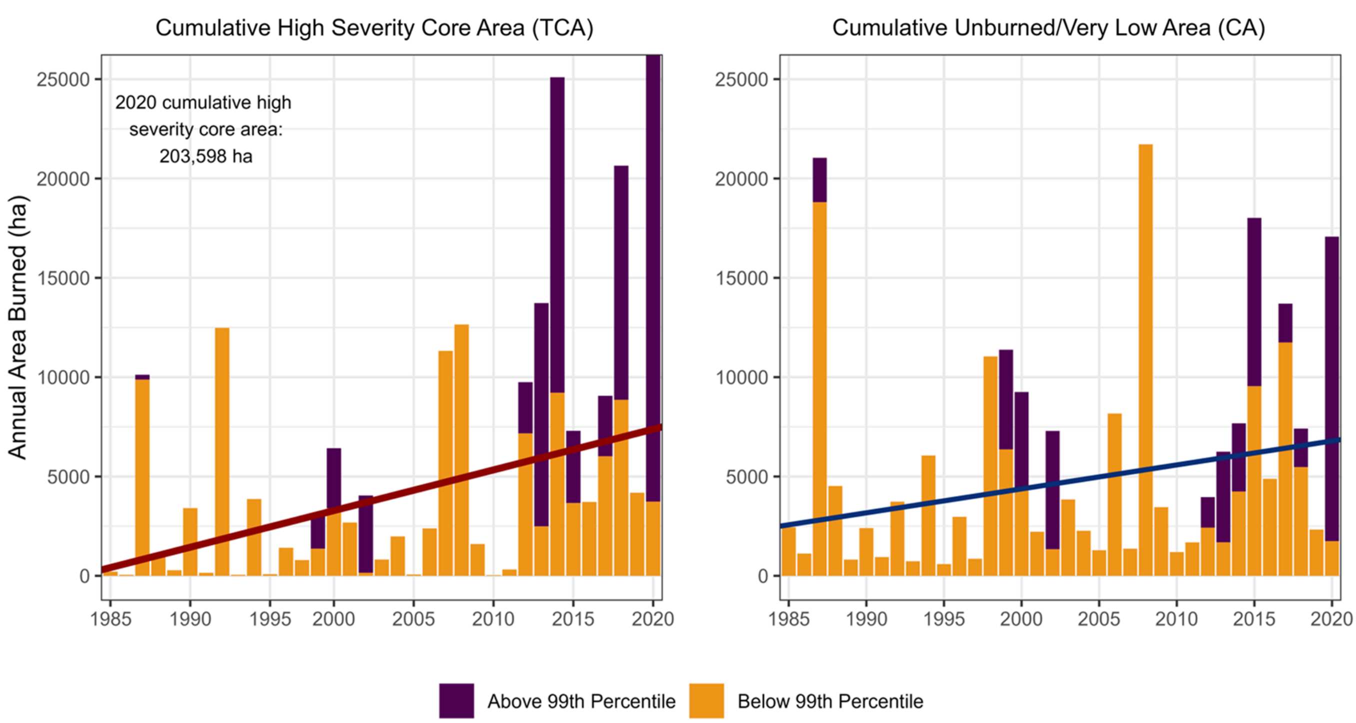

Fig. 6. Trends in total annual interior core area of high severity (TCA, left panel) and total annual unburned refugia-very low severity (CA, right panel) between 1985 and 2020 across the study area. Trend lines represent Theil-Sen slope estimations of high-severity core area (left panel, red line) and total unburned area (right panel, blue line). Note that for the year 2020, total core area burned at high severity (left panel) extends beyond the y-axis limits; the total amount is noted at the top left of the plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drought conditions and warmer temperatures, which are expected to intensify under a rapidly changing climate (Dennison et al., 2014; Holden et al., 2018; Westerling, 2016). If wildfires continue to burn dense, homogenized forests, annual area burned and mean fire size driven by rapid fire spread events are likely to continue increasing, and the exceptionally large fires included in this analysis may become more characteristic of future norms (Coop et al., 2022). Assessing the dynamics and drivers of these increases, including where reburned areas may exacerbate or mitigate subsequent fire severity, will be critical topics of future research as fire-on-fire interactions become more frequent.

It is important to note that increases in total annual area burned and fire size alone are not intrinsically a cause for concern. It is widely recognized that over a century of fire exclusion, including suppression policies and curtailment of Indigenous burning, has led to a profound fire deficit across much of California's forests (Hagmann et al., 2021; Hessburg et al., 2019; Mallek et al., 2013; Marlon et al., 2012; Parks et al., 2015). In areas with low to moderate overstory tree mortality

Table 5
Results of Theil-Sen slope estimator for total annual high-severity core area (TCA) burned and total annual unburned area (CA) between 1985 and 2020 across the study area. Slopes indicate the estimated annual increase (positive slopes) or decrease (negative slopes) in units of hectares. Asterisks indicate statistically significant trends.

	Z stat	Sen's slope (ha)	p-value	**1985 fit**	**2020 fit**
High-severity core area	3.04	204.87	0.00239*	211 ha	7,375 ha
All unburned-very low severity area	2.08	120.56	0.037*	2,448 ha	6,668 ha

following fire, increases in annual area burned certainly address this deficit. However, the observed spatial patterns of severity – including historically unprecedented trends in high-severity core area and patch size configurations – within recent exceptionally large fires suggest that these fires represent an emerging fire regime distinct from historical norms.

Specifically, we found that recent exceptionally large fires have higher mean burn severities than smaller fires, and contain large patches of all fire severities that leave behind markedly different patterns of forest structure than the fine-scale heterogeneity produced by historic fires (Collins & Roller, 2013; Fry et al., 2014; Perry et al., 2011). In areas of forest where these exceptionally large events were the first fire following an extended fire-free period – i.e., first-entry fires – these novel spatial patterns of fire severity may be self-reinforcing in future fires without appropriate post-fire management. In our study area, spatial patterns of fire severity tend to follow the patterns of previous wildfires – that is, in mixed conifer forests, low severity in previous fires typically begets low severity in subsequent fires, and areas that previously burned at high severity may subsequently burn at high severity due to accumulations of snags, coarse woody debris, and regeneration of flashy fuels such as shrubs and grasses (Parks et al., 2014; Prichard et al., 2017; Taylor et al., 2021, 2022). As areas within existing exceptionally large fires are reburned in subsequent wildfire, assessing whether these self-reinforcing patterns are present should be a focus of future work.

4.2. Spatial patterns of exceptionally large fires

We found that the largest fires (greater than the 95th and 99th percentiles by size) were distinct from the population of smaller fires in their proportions of area burned at different severities (Fig. 4). Unlike smaller fires, these largest fires contained relatively smaller proportions of unburned refugia and were dominated by area burned at low-moderate and high severity. The 18 exceptionally large fires, representing the top 1 percent of fires by size, were associated with greater proportions of high severity in particular, consistent with previous work that has found greater proportions of stand-replacing effects in large wildfires (Keane et al., 2008; Lydersen et al., 2014; Safford et al., 2022; Stephens et al., 2022; Taylor et al., 2022). These patterns reflect the extreme conditions in which these large fires have typically burned – for example, wind-driven or plume-dominated events such as the 2020 Creek fire exhibit extreme fire behavior under hot and dry conditions that often result in widespread tree mortality (Stephens et al., 2022).

Exceptionally large fires were responsible for the majority of high-severity fire effects across California forests (Table 5, Fig. 6), and our assessment of mean patch sizes suggests that these effects are concentrated in large, contiguous patches (Fig. 5). The top 1 percent of fires by size accounted for 58 percent of the cumulative area burned at high severity between 1985 and 2020 for a total of 620,307 ha. We found that exceptionally large fires contained larger mean high-severity patches than smaller fires regardless of whether arithmetic or area-weighted calculations were used, producing a distinct spatial signature uncharacteristic of the fine-scale patch heterogeneity historically found in fires prior to widespread fire exclusion (Fry et al., 2014; Perry et al., 2011, Safford & Stevens, 2017). These larger mean patch sizes in exceptionally large fires reflect the influence of both *overall* larger high-severity patches (i.e., even the smallest high-severity patches in large fires tend to be larger than those of smaller fires) and the presence of a handful of extremely large patches in exceptionally large fire events (i.e., the 2020 August Complex and Creek fires, which each contained homogenous high-severity patches roughly 20,000 ha in area (Stephens et al., 2022)). These large contiguous patches inherently contain greater interior core area, which is associated with increased distance to live seed source and likelihood of tree regeneration failure leading to persistent vegetation type-conversion, loss of carbon storage, and diminished wildlife habitat

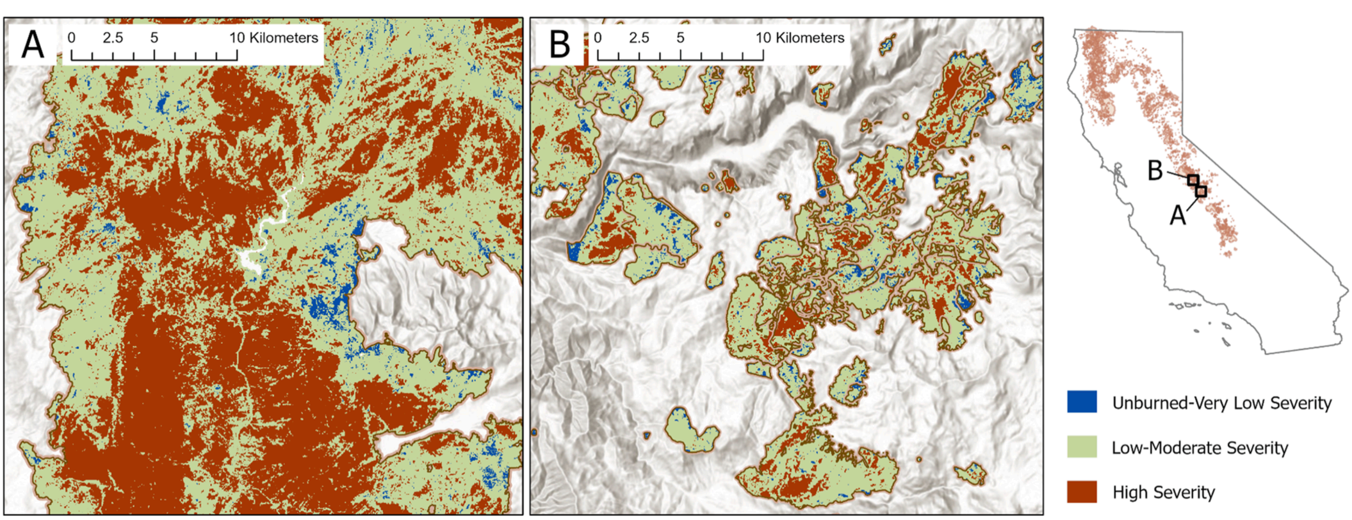

Fig. 7. Impacts of one exceptionally large fire (Panel A, left) versus dozens of smaller fires (Panel B, right) on California forests. Panel A shows the 2020 Creek Fire in the Sierra Nevada, which contains some of the largest single patches of high and low-moderate severity (greater than 20,000 ha) in this analysis. Panel B shows a mosaic of 80 small fires ranging from 4 ha to 3,470 ha that burned between 1985 and 2020 just south of Yosemite Valley in the Sierra Nevada. In both panels, dark blue represents unburned-very low severity, light green represents low-moderate severity, and dark red represents high severity. Both panels are at the same spatial scale and have the same areal extent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Earles et al., 2014; Stevens et al., 2017).

While their large stand-replacing patches and associated severe ecological consequences cannot be understated, we also found that exceptionally large wildfires were responsible for the majority of low- to moderate-severity fire effects. The largest 18 fires across the study period were responsible for 42 percent of the area burned with low to moderate severity effects across California forests, and the top 5 percent of fires by size were responsible for 74 percent. Smaller fires – though large in number – had a small cumulative impact by area. We found that exceptionally large fires contained large patches of low-moderate severity effects – often as large as their high-severity patches – suggesting that these fires leave behind contiguous areas of forest (see Fig. 7) with markedly different post-fire trajectories and management needs than from high-severity patches. It is important to note that our low-moderate severity category captures a broad range of fire effects, from consumption of predominantly understory vegetation with minimal effects on overstory trees to mortality of mid-sized trees resulting in significant reductions to live tree density (Collins et al., 2018; Lydersen et al., 2016). There is likely to be more forest structural heterogeneity within the low-moderate severity class than can be described by the categorization used in this study. Still, these effects mimic a range of treatments that cumulatively push forests closer to resilient conditions and positive ecological outcomes such as maintaining biodiversity and stabilizing carbon storage (Collins et al., 2017a, 2017b, 2018; Stephens et al., 2020).

Because smaller fires inherently contain less area for large patches, large fires would be expected to contain larger mean patch sizes. We therefore do not suggest that higher mean patch sizes in larger fires is unusual, but rather underscore the novel ecological impacts of their size and spatial patterns. For example, fine-scale mosaics of unburned, low-moderate, and high severity patches in smaller fires shape heterogeneous patterns of individual trees, tree clumps, and openings that can impede the spread of pathogens and insect outbreaks across a forest stand (Churchill et al., 2013; Fettig et al., 2007; Goheen & Hansen, 1993). Forest structural heterogeneity additionally provides a variety of habitat niches that enhance species richness, persistence, and opportunities for divergent adaptations of plant and animal species (Laszlo et al., 2018; Stein et al., 2014; Tews et al., 2004; Weisberg et al., 2014). Fires dominated by larger patches fundamentally shape forests at a much coarser scale, and though a range of post-fire ecological effects may still be present within the full fire perimeter, their configurations may fail to support the biodiversity and ecological processes that benefit from finer-scale mosaics (Fig. 7) (North et al., 2009).

Although our 18 largest fires share common characteristics such as large patch sizes, they are still distinct in their individual ecological signatures based on their proportions of burn severities (Table 1, Fig. 4) and warrant evaluation on a case-by-case basis. There are a number of reasons why a fire may become exceptionally large. For example, the 2013 Rim fire – the fourth largest fire in this study – partially burned under extreme conditions and 35 percent of the fire's total area burned within a two-day period (Povak et al., 2020). By contrast, the 2020 August Complex fire, which is both the largest fire in this study and the largest fire on record for all of California, originated as 38 separate lightning-ignited fires that eventually coalesced over the course of several weeks (National Weather Service - Eureka Office, 2021). The second largest fire in this study, the 2020 Creek fire, burned rapidly through severely drought-affected forests but experienced its greatest growth on days largely within the normal range of variation for weather at the time of burning (Stephens et al., 2022). Due to the broad spatial extent and temporal breadth of our study, our dataset captures a range of burning conditions and incident response scenarios that directly inform resulting patterns of fire severity. Regardless of their size, each exceptionally large wildfire shaped forests in distinct ways and warrant discrete post-fire management strategies.

4.3. Temporal trends in high-severity fire effects and unburned area

Across the 36-year study period, we observed sharp increases in the interior core area of high-severity fire effects (Fig. 6). The 18 exceptionally large wildfires within our study were responsible for a majority – 68 percent – of this total over the entire study period. This is somewhat expected, because large fires generally burned under more extreme fire weather conditions than small fires (Meyer, 2015; Singleton et al., 2021; Steel et al., 2018; Stevens et al., 2017). Extreme burning conditions that result in large, contiguous areas of overstory tree mortality are often the same conditions that escape initial fire suppression response and result in days of large fire spread (Coop et al., 2022). Cumulatively, smaller fires were responsible for only a minor portion of the total core area of high-severity fire, in part due to their small size and more moderate weather conditions under which they typically burned.

Though we observed relatively low proportions of unburned area in exceptionally large wildfires, our Theil-Sen slope analysis revealed statistically significant increases in total annual area of unburned refugia over the study period. This increase largely reflects coincident increases in total annual area burned, as large fires tended to have larger patches across all severity classes, including unburned islands. Although cumulative area of unburned refugia increased over the study period, it increased at about half the rate as increases to high-severity interior core area. These unburned islands – though they technically occupied more area in 2020 than they did in 1985 – are still overwhelmed by surrounding high-severity patches in exceptionally large fires (Fig. 7). Our results suggest that although the extent of unburned refugia has increased over time, these patches may grow increasingly fragmented and isolated as annual area burned and fire sizes continue to increase. This is consistent with Steel et al. (2018), who found that patches of unburned refugia in California mixed-conifer fires that burned between 1984 and 2015 have become increasingly disaggregated.

Although this study focused on fires within California conifer forests, the spatial and temporal patterns identified in our analyses are consistent with broader regional trends across western North American forests. Increasing high-severity patch sizes and increased homogenization of patch structures in large fires that burned between 1984 and 2008 were identified in the northern Cascade Range of Washington state (Cansler & McKenzie, 2014). Across warm and dry conifer forests in the broader Pacific Northwest, proportions of high-severity effects in fires that burned between 1985 and 2010 were greater than historical ranges of variation, and nearly half of this high-severity area occurred in large patches greater than 100 ha (Reilly et al., 2017). In the northern Rocky Mountains, trends in high-severity patch structures within fires that burned between 1984 and 2010 suggested shifts towards larger, more homogenous patches with greater interior core area, though they were not statistically significant (Harvey et al., 2016). Given recent increases in annual area burned and mean fire severity (Parks & Abatzoglou, 2020) and a number of record-breaking large fires across western North American forests since the aforementioned studies were conducted, the ecological implications of our findings – presented here within the context of California forests – may be more broadly applicable to warm and dry, fire-suppressed conifer forests across the west.

4.4. Management implications

Coarser-scale patterns of fire severity on the order of hundreds to thousands of hectares – like those of the exceptionally large wildfires in this study – are significantly departed from the natural range of variation of frequent fire regimes in our study area. Modern studies in US National Parks with restored fire regimes (Collins et al., 2007) and analysis of historical forest conditions prior to widespread fire exclusion (Safford & Stevens, 2017) suggest that California dry mixed-conifer forests frequently burned in complex mosaics of unburned, low-, moderate-, and high-severity patches typically no larger than a few hectares. These patch mosaics shaped patterns of highly heterogeneous forest structure that regulated the forest's ability to maintain function following subsequent disturbances (Koontz et al., 2020). Small patches of previously burned areas served as 'fences' to subsequent fire spread, and unburned areas or areas of forest that had not recently burned acted as 'corridors' of fire spread, reinforcing a shifting mosaic of forest structures and a regime of frequent, predominately low- to moderate-severity fire (Moritz et al., 2011). As larger fires produce coarser-grained patterns of severity, these patterns may become self-reinforcing, and the ecological memory of forests rooted in fine-scale self-regulation may begin to erode (Taylor et al., 2021).

In frequent-fire ecosystems, historic fire regimes often set the scale and habitat variability that influences the evolution of ecological processes and endemic wildlife (Falk et al., 2011; Pausas & Parr, 2018). Shifting landscape patterns induced by changes in patch sizes may have cascading effects on ecological processes that are associated with fine-scale structural heterogeneity. Forest structural diversity, for example, drives microclimates that regulate subcanopy temperatures, snowpack accumulation and ablation, and thermal refuges, in turn influencing water availability, soil nutrient cycling, plant species biodiversity, and habitat suitability for small terrestrial animals (Kemp et al., 2014; Milling et al., 2018; Tews et al., 2004; Varhola et al., 2010; Wolf et al., 2021). As patterns of structural heterogeneity coarsen, this patchwork of microclimates may erode, fragmenting wildlife habitat, threatening keystone species, and altering understory vegetation composition (Jones et al., 2020; Steel et al., 2022a; Stephens et al., 2021).

While exceptionally large fires often burned with low- to moderate-severity effects, the landscape pattern of burned areas represents a novel configuration for which there is no historical analog. Recent studies have underscored the importance of post-wildfire management responses to these novel landscapes, including post-burn thinning, fuel reduction, and variable-density tree planting (Meyer et al. 2021; North et al., 2019; Stevens et al., 2021). Post-fire patch sizes and configurations are also important considerations for adaptive management (Hessburg et al., 2016, 2019). Introducing additional structural variation at finer spatial scales will be a critical component of adaptive management, not only within patches that burned at high severity but also within unburned islands and areas that burned at low and moderate severity that are outside the range of variation for historical patch sizes. More pre- and post-burn fuel reduction, particularly with prescribed fires for its creation of 'fence' and 'corridor' heterogeneity, may be the most durable and effective means of reducing the self-reinforcing pattern of large high-severity patches (Knapp et al. 2017, Taylor et al., 2022).

These large fires with their unprecedented patch sizes create new challenges and potential opportunities for managers. For the past three decades, much of the focus in the scientific literature and management discussion has been on increasing the pace and scale of treatments to reduce tree density and fuels left by a century of logging and fire exclusion. However, this study demonstrates that the rapidly increasing area and severity of recent wildfires overwhelms the area treated by management agencies (North et al. 2021). While much of the current post-fire management focus has been on salvage logging and replanting in high-severity patches, these large fires have also left extensive forest swaths of low- to moderate-burn severities. In these areas, managers could leverage the wildfire's 'work', and use thinning to remove remaining ladder fuels (Collins et al. 2018) and create or accentuate the spatial pattern of individual trees, clumps of trees, and openings (i.e., ICO, Churchill et al. 2013), that increases forest resilience to wildfire (Koontz et al. 2020, Ng et al., 2020). Seven to twelve years after the fire, when large fuels accumulate as snags fall over, prescribed fire could be applied to reduce surface fuels (Ritchie et al. 2013). With this additional fuel reduction 'hardening' of the low-moderate severity patches, they could be used as anchors for wider use of managed wildfire or prescribed burns, implementing a pyrosilviculture approach to landscape management (North et al. 2021).

5. Conclusion

Exceptionally large fires are complex and contain a range of both desirable and undesirable ecological effects on California forests. The largest fires in our analysis contained proportionally greater amounts of high-severity fire and contributed to significant increases in high-severity interior core area, but were also responsible for the vast majority of low-moderate severity effects that reshape and can help restore resilience to mixed-conifer forests (Collins et al., 2011). Configurations of very large high-severity and low-moderate-severity patches with little area of unburned refugia represent an emerging fire regime that may alter the fine-scale forest structural heterogeneity historically created by smaller fires. Because fires in our study area tend to follow the spatial patterns of previous fires (Parks et al., 2014; Prichard et al., 2017; Taylor et al., 2022), future fire patterns may become self-reinforcing, further eroding fine-scale mosaics of forest structure heterogeneity. These post-fire landscapes may present novel challenges for forest managers as they leave behind large, contiguous areas of stand-replacing fire and yet also contain patches of low- and moderate-severity effects that, with subsequent targeted fuels reduction, can move burned forests towards greater resilience to climate change and future fire events.

CRediT authorship contribution statement

Gina Cova: Conceptualization, Methodology, Investigation, Visualization, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Van R. Kane:** Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing. **Susan Prichard:** Methodology, Writing - original draft, Writing - review & editing. **Malcolm North:** Methodology, Writing - original draft, Writing - review & editing. **C. Alina Cansler:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data supporting results is available on request to corresponding author.

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