Research Article

Patterns and Trends in Burned Area and Fire Severity from 1984 to 2010 in the Sierra de San Pedro Mártir, Baja California, Mexico

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ABSTRACT

Yellow pine (*Pinus* spp. L.) and mixed conifer (YPMC) forests of California, USA (Alta California), have been negatively affected since Euro-American settlement by a century or more of logging, fire exclusion, and other human activities. The YPMC forests in northwestern Mexico (northern Baja California) are found in the same climate zone as those of Alta California and support mostly the same dominant species, yet they are much less degraded, having suffered little logging and only 30 years of fire suppression. As such, the Baja California forests are believed to more closely approximate pre-Euro-American settlement conditions, and they have been proposed as reference ecosystems for restoration and management of Alta California forests. We studied fire severity trends in the Sierra de San Pedro Mártir National Park

RESUMEN

Los bosques de pino amarillo (*Pinus* spp. L.) y de coníferas mixtas (PACM) de California, EEUU (Alta California), han sido afectados negativamente desde el establecimiento de los euro-americanos debido a un siglo o más de explotación forestal, de supresión de fuegos y otras actividades. Los bosques (PACM) en el noroeste de México (norte de Baja California) se encuentran en la misma zona climática que los de Alta California, tienen la mayoría de sus especies dominantes, están menos degradados debido a que presentan poca actividad de explotación forestal y solo 30 años de supresión de fuego. Por lo anterior, se cree que los bosques de Baja California se asemejan a las condiciones que presentaban previo al establecimiento de los euro-americanos, y pueden ser propuestos como ecosistemas de referencia para la restauración y manejo de los bosques de Alta California. Nosotros estudiamos las tendencias en la severidad del fuego en el Parque

(SSPMNP), which supports the largest area of YPMC forest in Baja California, to determine whether fire severity is rising over the last three decades in the same manner that it is rising in the Sierra Nevada of Alta California. We used LANDSAT data to identify 32 fires that burned 26 529 ha in the Sierra de San Pedro Mártir National Park in the period 1984 to 2010. Of this, 1993 ha burned in YPMC forest types in 17 fires. We found no temporal trends in forest burned area or in the proportion of high severity fire, but we did find that the mean size of high severity patches within fires is rising. In the SSPMNP, the overall proportion of fire area burned at high severity averaged 3 % in both yellow pine and mixed conifer forests. We found no significant autoregressive effects of year in any of our analyses, but the year with the most burned area occurred after drier-than-average periods. In the SSPMNP data, there was no correlation between burned area and proportion of high severity fire; we interpreted this to mean that differences in fuels in SSPMNP were more important to fire behavior than weather conditions. The SSPMNP continues to burn at very low severities, even after 30 years of effective suppression of lightning-ignited fires. This is in stark contrast to similar forests in Alta California, which are experiencing fires of sizes and severities that fall far outside the historical range of variation. Current fire severities in the SSPMNP are very similar to the levels of severity described for Alta California YPMC forests before Euro-American settlement. Nonetheless, fire suppression policies in Mexican national parks in northern Baja California are causing increases in forest fuels and may be the cause of

Nacional Sierra San Pedro Mártir (PNSSPM), el cual tiene la mayor área de bosque de PACM en Baja California, para determinar si esta severidad está aumentando en las tres últimas décadas de la misma manera que lo está haciendo en la Sierra Nevada de Alta California. Se utilizaron datos LANDSAT para identificar 32 incendios que quemaron 26 529 ha en el Parque Nacional Sierra de San Pedro Mártir en el periodo de 1984 a 2010. De éstas, 1993 ha corresponden a vegetación de bosque PACM quemado en 17 incendios. No se encontró una tendencia temporal en el área de bosque quemado o en la proporción de incendios de alta severidad, pero sí se observó que el tamaño medio de parches de alta severidad en los incendios está aumentando. En el PNSSPM, el promedio de área quemada con alta severidad fue de 3 % en los bosques de pino amarillo y de PACM. No se encontraron efectos significativos en la autoregresión entre años en ninguno de los análisis, pero el año con más área quemada ocurrió después de un período más seco que el promedio. En los datos del PNSSPM, no hay correlación entre el área quemada y la proporción de fuegos de alta severidad; los datos sugieren que las diferencias entre combustibles en el PNSSPM son más importantes para el comportamiento del fuego que las condiciones climáticas. El PNSSPM presenta niveles de baja severidad incluso 30 años después de una efectiva supresión de incendios iniciados por rayos. Esto contrasta altamente con lo que ocurre con bosques similares en Alta California, los cuales experimentan tamaños de incendios y severidad mayores a la variación del rango histórico. La severidad actual de fuego en el PNSSPM es muy similar a los niveles de severidad reportados para Alta California en bosques de PACM antes de la llegada y establecimiento de los primeros euro-americanos. A pesar de ello, las políticas de supresión actuales en los parques mexicanos en el norte de Baja California están causando la acumulación de combustibles forestales, que pueden ser la causa recent increases in high severity patch size. Current wildfire trends in YPMC forests in Alta California should serve as a warning to Mexican managers that continued fire exclusion in the Baja California YPMC forests is a recipe for ecological disaster in these unique and important ecosystems.

del incremento reciente en los parches de alta severidad. La tendencia actual de los incendios forestales en bosques de PACM en Alta California debería servir como advertencia para los gestores mexicanos, dado que la continua supresión de fuego en los bosques de PACM en Baja California es una receta que los llevará al desastre ecológico en esos únicos e importantes ecosistemas.

Keywords: Alta California, Baja California, fire severity, management, mixed conifer, Sierra Nevada, Sierra de San Pedro Mártir, yellow pine

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INTRODUCTION

Studies of semi-arid forests in western North America show that, before the arrival of Europeans, fire was a common and important ecological process. In the mediterranean-climate region of the continent (which corresponds to the California Floristic Province), forests dominated by yellow pines (ponderosa pine [*Pinus ponderosa* Lawson & C. Lawson], Jeffrey pine [*P. jeffreyi* Balf.]) and mixtures of these with other tree species burned on average every decade or two, with fires dominated by low severity effects (Agee 1993, Stephens *et al*. 2003, Van de Water and Safford 2011). After they settled in California, USA, Euro-Americans began to extinguish light fires whenever and wherever possible, as it was thought that such fires damaged the forest and timber resources. Today, long-term fire suppression in yellow pine and mixed conifer (YPMC) forests has resulted in great alterations to the fire regime and forest structure (Agee 1993, Sugihara *et al.* 2006, Safford and Stevens 2016). The lack of low severity fire in a region with very slow biological decomposition rates (Murphy *et al*. 1998) has resulted in an accumulation of dead and live organic material, changing the structure and density of the forest, and greatly increasing fuel loads (Steel *et al.* 2015, Safford and Stevens 2016). Fire suppression practices in California were originally held as an example for other countries to follow (Stephens and Ruth 2005), but since then, the ecological consequences of the practice have begun to manifest themselves in more extensive and more severe forest fires, among other ecological problems (Miller *et al*. 2009*b*, Miller and Safford 2012).

The states of Baja California, Mexico, and California, USA, (Alta California) both belong partially to the California Floristic Province and they share many ecosystems with similar species and climates (Minnich *et al*. 2000, Delgadillo 2004). The Sierra de San Pedro Mártir National Park (SSPSNP) hosts YPMC forests—in this case dominated by Jeffrey pine—that are floristically and ecologically similar to forests in semi-arid areas of Alta California in the south of the state and on the eastern side of the Sierra Nevada (Stephens *et al*. 2003, Dunbar-Irwin and Safford 2016). However, forest structural conditions in the Sierra de San Pedro Mártir National Park are very different from conditions in Alta California, as a century of fire exclusion and 150 years of logging have led to denser and younger forests in Alta California that are lacking most of the large trees that used to comprise most of the biomass (van Wagtendonk and

Fites-Kaufman 2006, Fites-Kaufman *et al*. 2007, Stephens *et al.* 2015). In contrast, the SSPMNP is notable for having suffered little to no logging in the past and having only a recent history of fire suppression (~30 yr; Minnich *et al*. 2000, Stephens *et al*. 2003). As a result, the fire regime and forest overstory conditions in the SSPMNP are relatively little altered from their natural state, and the SSPMNP serves as an important reference site for management and restoration of similar but more degraded forest ecosystems in Alta California (Stephens and Fulé 2005, Stephens *et al*. 2008, Dunbar-Irwin and Safford 2016).

Many mediterranean-climate ecosystems in Mexico are classified as fire dependent (Shlisky *et al*. 2007, Trejo 2008). This is to say that the component species have lived and evolved with the presence of fire, and that fire plays many important ecological roles in the ecosystem. In the case of YPMC forests in the California Floristic Province, frequent low to moderate severity fire recycles nutrients, reduces fuel, provides mineral seed beds for the regeneration of seedlings, and helps fire tolerant tree species maintain their dominance in the stand (Mallek *et al*. 2013). Fire also generates scars in the bark and wood of trees, leaving traces of its passage and allowing for the reconstruction of past fire regimes. Through this fire record it is known that, for centuries, the forests of the SSPMNP have experienced fires at mean intervals of less than 15 years (Stephens *et al*. 2003). Currently however, the SSPMNP practices a policy of total suppression of fires, and this policy has been effective in extinguishing almost all fires over the last three decades. Today, the occurrence of fire in the forests of the SSPMNP is a rare event.

In the SSPMNP, dendrochronological studies have been made to determine the historical fire regime, its timing, occurrence, and spatial complexity (Stephens *et al*. 2003). Other studies have used aerial photographs to reconstruct fire area and the effects of fire on forest structure in mid- to late-twentieth century fires (Minnich 2000). Today the Mexican National Forest Commission (CONAFOR) generates reports on fire events, the type of vegetation affected, and the location of the burn perimeter, but this practice only began in 2010; prior to that, only an approximate geographic location and name were collected. The advent of remotely sensed LANDSAT-Thematic Mapper (TM) based fire severity measurements (Miller and Thode 2007; Miller *et al*. 2009*a, b*) allows an assessment of more modern fires from the context of their effects on forest ecosystems.

In this study, our general objectives were to (1) provide a broad description of temporal and spatial patterns in fire severity in YPMC forests of the Sierra de San Pedro Mártir, and (2) to compare these patterns with those in more degraded forests in Alta California. Specifically, we used LANDSAT data to describe the effects of fire severity in conifer forests in the SSPMNP in the period 1984 to 2010 to ascertain (1) whether there are temporal trends in fire severity and high severity patch size in the SSPMNP, because the park now enforces a policy of strict fire suppression, the same that has contributed to increasing severity trends in Alta California; and (2) if there are noteworthy differences in fire severity patterns and trends in SSPMNP forests versus similar forests in Alta California.

METHODS

Study Area

The Sierra de San Pedro Mártir National Park (72 911 ha) is located approximately 130 km southeast of the city of Ensenada (Figure 1). The SSPMNP belongs to the Peninsular Range, which stretches from southern Alta California to the southern tip of Baja California, and includes the highest point in Baja California (Picacho del Diablo, 3096 m). Climatically, winters in the SSPMNP are cool and moist, and summers are warm and dry. January mean minimum temperatures at 2080 m

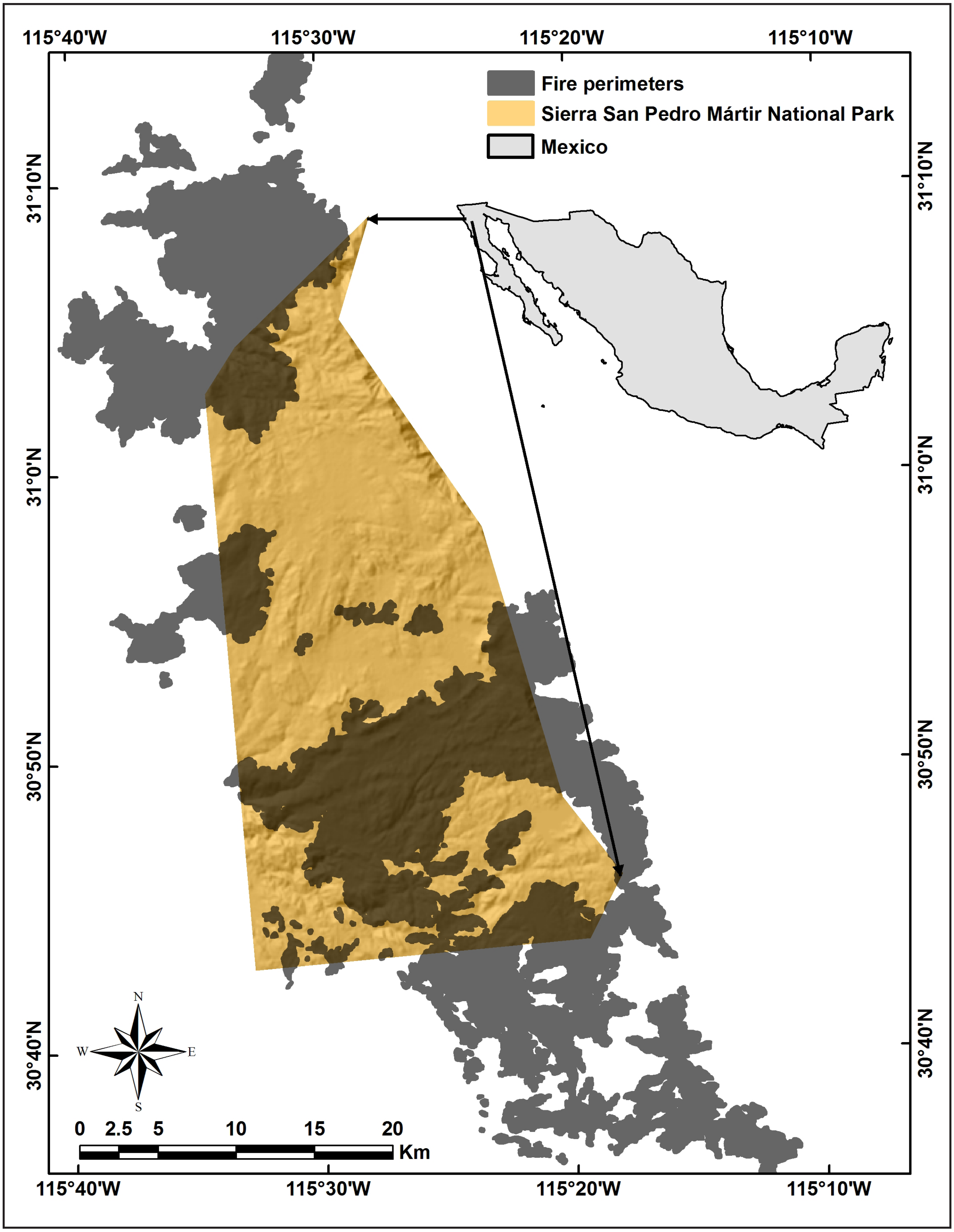

Figure 1. Sierra de San Pedro Mártir National Park. The park is found within the tan colored polygon. Gray polygons represent 49 fire perimeters that burned in or near the park between 1984 and 2010.

are about −1.0 °C, and July mean maximum temperatures are about 24.9 °C. Mean annual precipitation is about 570 mm, most of which falls as snow in the winter months; 10 % to 20 % of precipitation falls during the summer monsoon season (Dunbar-Irwin and Safford 2016). Geologically, the SSPMNP is mainly underlain by granitic rocks, with some areas of metamorphic rock (Stephens *et al*. 2003). Forest soils are mostly sandy, with somewhat more clay in soils formed from metamorphic rocks and in riparian settings.

Coniferous forest in the SSPMNP ranges from about 2000 m to 2900 m with scattered trees found on rocky slopes above this elevation and in riparian areas below. Minnich *et al*. (2000) estimated forest coverage in the SSPMNP at about 40 000 ha, but US Forest Service mapping shows about 17 000 ha of forest (defined as ≥10 % tree cover) within the park itself, or about 23 % of the park area. In the YPMC forests, principal species include Jeffrey pine, white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), sugar pine (*Pinus lambertiana* Douglas), and canyon live oak (*Quercus chrysolepis* Liebm.). Lodgepole pine (*P. contorta* Douglas ex Loudon var. *murrayana* [Balf.] Engelm.) is common around meadows, in riparian areas, and at higher elevations, and some Coulter pine (*P. coulteri* D. Don) is found at lower elevations, usually mixed with chaparral. Other mostly riparian species include aspen (*Populus tremuloides* Michx.), which is also found on lower parts of some north facing slopes, and incense cedar (*Calocedrus decurrens* [Torr.] Florin). Jeffrey pine-dominated forests are open canopied, with cover mostly ranging from 10 % to 35 %. Mixed conifer stands tend to be somewhat denser, and white fir-sugar pine stands on north facing slopes may support canopy covers of 45 % or more. Forest densities are much lower than in most Jeffrey pine or mixed conifer stands in Alta California. Dunbar-Irwin and Safford (2016) found that stands in the northern part of the park supported about 188 trees ha^{-1} (>7.6 cm dbh), whereas forests in the eastern Sierra Nevada of Alta California that had similar composition and climate supported a mean of 352 trees ha^{-1}. Stands in the SSPMNP also support less biomass: mean live basal area (BA) was about 30 % lower in the SSPMNP than in the eastern Sierra Nevada (22.5 m^2 ha^{-1} versus 31.8 m^2 ha^{-1}; Dunbar-Irwin and Safford 2016).

The mean historic fire return interval reported for YPMC stands in the northern part of the park was about 15 yr (Stephens *et al*. 2003), comparable to mean pre-Euro-American settlement fire return intervals for similar forests in southern California and the Sierra Nevada (Stephens *et al.* 2003, Van de Water and Safford 2011). It was also reported that 90 % of the fire scars were located in the early annual growth, suggesting that most fires took place in the early summer (June to August; Stephens *et al*. 2003, Skinner *et al*. 2008). This seasonality is associated with the North American monsoon (Minnich *et al*. 2000, Skinner *et al*. 2008), which brings rain and lightning to the SSPMNP area during the otherwise dry summer (Minnich *et al*. 1993).

SSPMNP Vegetation Map

The existing vegetation map for the Sierra de San Pedro Mártir National Park was developed by the Remote Sensing Lab of the Forest Service Pacific Southwest Region in 2010 and 2011. The mapping protocol followed standard US agency mapping methods, and was based on 2007 Quickbird (DigitalGlobe, Westminster, Colorado, USA) imagery (85 % of the park; 2.4 m resolution for the multispectral band, 0.6 m resolution for panchromatic) and 2010 SPOT imagery (15 % of the park; 10 m resolution). The minimum mapping unit was 0.4 ha. Field plots were collected in 2010 to train the classification and develop species distribution models. A summary of the mapping protocol (Baja California Map User Guide) can be found at http://www.fs.fed.us/r5/rsl/

projects/gis/data/baja/, and the geodatabase itself, as well as the geodatabase of the vegetation map for the Sierra de San Pedro Mártir National Park, can be obtained from the corresponding author.

Within the park, mapping determined that forested areas (≥10% tree cover) summed to 16 937 ha, or 23.2% of the park. Shrublands covered about 58% of the park, grasslands and other herbaceous vegetation 13%, and rock and other unvegetated lands summed to about 5%.

Remote Sensing

Fire perimeters. The CONAFOR fire ignition dates and fire perimeters were not available to identify fires that occurred in 2010 or before. Two LANDSAT images for each calendar year between 1984 and 2010, one from late spring (May to June) and the other from early fall (September to October), were visually examined to identify fire locations. We did not analyze years after 2010 because no fires more than 10 ha in size occurred between 2010 and 2015. Fire perimeters were digitized from RdNBR (relative differenced normalized burn ratio; Miller and Thode 2007) images derived from the earliest possible post-fire image and a pre-fire image with a matching pre-fire date. To ensure consistency and high spatial precision, digitization was performed at on-screen display scales between 1:12 000 and 1:24 000.

Forest baseline establishment for fire severity assessment. Because the SSPMNP vegetation map was developed with 2007 and 2008 imagery, it was necessary to establish a baseline of where forest did and did not exist at the beginning of our fire severity time series, which began in 1984. We acquired 1:50 000 digital black and white aerial photos for the SSPMNP for the year 1972 from the Instituto Nacional de Estadística y Geografía (INEGI). The photos were georeferenced in a GIS program (ArcGIS v. 10.2; ESRI®, Redlands, California, USA) using at least 100 control points per photo; additional control points were added to historic images as needed. Polygons were added to the feature class via hand digitization and three classes were created: (1) forest (≥10% tree cover), (2) non forest, and (3) no data (e.g., where there were deep shadows in the image). A minimum patch size of 0.4 ha was used.

Fire severity. Severity of fires was mapped using satellite images. Although we mapped severity for all vegetation types in the SSPMNP, here we only reported severity for forest types that fit within the general description of yellow pine and mixed conifer forest. This included the CALVEG (USDA Forest Service, Region 5, Vallejo, California, USA, vegetation classification system) types JP (Jeffrey pine), MF (mixed conifer-fir), and WF (white fir), and some polygons of PQ (singleleaf pinyon [*Pinus monophylla* Torr. & Frém.]) that included an important component of Jeffrey pine. Because fires can affect vegetation type (for example, high severity fires in YPMC forests in the California Floristic Province often create vegetation transitions from forest to montane chaparral for periods of many decades), we used the forest baseline polygons from before 1984 (see preceding section) to spatially constrain forest extent in our severity analysis.

All images were acquired by LANDSAT-Thematic Mapper (TM) and geometrically registered using terrain correction algorithms (Level 1T) by the United States Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center. We converted all satellite data to at-sensor-reflectance (Chander *et al*. 2009).

To identify fire perimeters and map severity, we used the normalized burn ratio (NBR) that is widely used in the United States for detecting burned areas and mapping severity (Eidenshink *et al*. 2007). The NBR is formulated using LANDSAT TM mid-infrared bands 4 and 7 (similar spectral bands for LANDSAT 8 are numbered 5 and 7):

$$NBR = \left(\frac{band\,4 - band\,7}{band\,4 + band\,7} \right) \quad (1)$$

Bands 4 and 7 are used because their difference typically shows the largest change between pre- and post-fire images (Miller and Yool 2002, Key and Benson 2006). Band 4 encompasses near-infrared 0.76 µm to 0.90 µm wavelengths, which are primarily sensitive to the chlorophyll content of live vegetation. Band 7, which records middle infrared 2.08 µm to 2.35 µm wavelengths, is sensitive to water content in both soils and vegetation, the lignin content of non-photosynthetic vegetation, and hydrous minerals such as clay, mica, and some oxides and sulfates (Elvidge 1990, Avery and Berlin 1992). NBR values generally range between 1 and −1.

Change detection methodologies that employ pre- and post-fire images have been shown to reduce confusion between burned areas and areas that were barren prior to the fire (Key 2006). To account for barren areas, we used the relativized differenced NBR (RdNBR) change index (Miller and Thode 2007):

$$RdNBR = \left(\frac{(PreFireNBR - PostFireNBR) - offest}{SquareRoot(ABS(PreFireNBR/1000))} \right) \quad (2)$$

To ensure that the mean of RdNBR values for unburned areas is zero, the mean of the differenced NBR (dNBR) values (i.e., *PreFireNBR − PostFireNBR*) was first computed for a sample of dNBR values outside the fire perimeter (*offset* in the above equation) (Key and Benson 2006, Miller and Thode 2007). Conforming to general practice, we also scaled NBR by 1000 to transform the data to integer format (Key and Benson 2006). Therefore, the pre-fire NBR was divided by 1000 in the RdNBR formula. Positive RdNBR values represent a decrease in vegetation cover while negative values represent increased vegetation cover.

Post-fire images were acquired during the summer of the year following each fire and pre-fire images were from either the year prior to the fire or during the same year as the fire. Conforming to best practices for a change detection methodology, we chose pre- and post-fire images with the best possible matching pre-fire dates to minimize differences in sun angle and phenology (Singh 1989).

One important aspect to using a relative index such as RdNBR is that, because different pre-fire vegetation conditions are compensated for by dividing by a function of the pre-fire NBR, RdNBR values can be compared between multiple fires across space and time. Therefore, calibrations to field measured values acquired in one fire can be applied to other fires (Miller and Thode 2007, Miller *et al.* 2009*a*). The RdNBR values for all fires were converted to units of composite burn index (CBI), percent BA change, and percent change in canopy cover based upon calibrations developed for similar forest types in Alta California (Miller *et al*. 2009*a*). The CBI is a field based protocol used in the United States that results in a severity rating of 0 to 3 (unburned to high; Key and Benson 2006). In this work, we used percent BA change, employing a threshold of ≥90% BA change to indicate areas of high severity (Table 1). We decided to use the percent BA change severity metric because our field sampling methods used common stand examine procedures that measured tree mortality, our tree species are similar to those used in creating the RdNBR calibration (Miller *et al.* 2009*b*), and tree mortality is

Table 1. Basal area change severity categories and associated RdNBR thresholds.

Severity	Basal area change	RdNBR
Unchanged	0%	<167
Low	>0% and <25%	≥167 and <370
Moderate	≥25% and <90%	≥370 and <652
High	≥90%	≥652

more easily understood by managers than a composite index like CBI that combines effects on overstory, understory, and soil. The RdNBR value for ≥90 % BA change (652) is very similar to the RdNBR value for the CBI rating of ≥2.25 (641), which has previously been used in numerous severity assessments in Alta California (Miller *et al*. 2009*a*, Miller *et al*. 2009*b*, Miller and Safford 2012, Mallek *et al*. 2013). Field verification of the BA change maps in the Sierra Nevada demonstrates that >85 % of plots >30 m (the width of a LANDSAT pixel) inside of high severity (≥90 % BA change) polygons do not have any live trees (Miller and Quayle 2015). Our high severity class is thus indicative of areas of stand-replacing fire. Areas in which the satellite images did not reveal any change one year post fire were mapped as unchanged (0 %), however they still may have experienced surface fire (Miller and Thode 2007, Miller *et al.* 2009*b*).

High severity patch size. We calculated the areas of all patches of high severity fire that occurred in the fires we analyzed. Minimum measurable patch size was 900 m^2, due to the LANDSAT 30 m pixel.

Trend analysis. We fit autoregressive integrated moving average (ARIMA) time domain regressions to burned area and the fire severity data (percentage of fire area burning at high severity and high severity patch size) using Box-Jenkins techniques for model identification and estimation; we compared model goodness-of-fit using the Akaike Information Criterion (Shumway 1988). All severity data were transformed by arcsin-square root and all area data by $\log_{10}$ to meet statistical assumptions of normality. In the end, none of the autoregressive functions were statistically significant for any of the three dependent variables, so the reported regressions are linear (Table 2).

RESULTS

Area Burned from 1984 to 2010

Within the perimeter of the Sierra de San Pedro Mártir National Park, we identified 32 fires that burned an area of 26 529 ha in the period from1984 to 2010. Most of the burned area was in chaparral vegetation. We analyzed 1993 ha that burned in forest types in 17 fires (Table 3). Over the 27 years of our study period, this results in a current fire rotation period

Table 2. Regression statistics for results of ARIMA time series modeling of burned area, fire severity, and high severity patch size from 1984 to 2010*.

	Burned area[1]	Percent high severity[2]	High severity patch size[3]
N	23	12	11
Error degrees of freedom	21	10	9
Parameter estimates			
Intercept	–145.779	–4.518	–160.608
Year	0.073	0.002	0.080
F	2.559	0.150	8.413
P (linear)	0.125	0.706	0.018
Statistics of fit			
Root mean square error	1.456	0.146	0.664
R^2	0.109	0.015	0.483
R^2 (adj)	0.066	–0.084	0.426

*None of the autoregressive functions were significant, so the regressions are linear.
[1] log x + 0.1 transformed
[2] arcsin-square root transformed
[3] log transformed

Table 3. Numbers of forest fires, areas (ha), and percentages of area burned by fire severity class in Jeffrey pine and mixed conifer forests in the Sierra de San Pedro Mártir National Park between 1984 and 2010.

		Fire severity class (area of basal area change)								
Year	Number of fires	Not changed 0 %	>0 % to <10 %	≥10 % to <25 %	≥25 % to <50 %	≥50 % to <75 %	≥75 % to <90 %	High ≥90 %	Total area burned (ha)	High severity as % of total area
1985	1	0.00	0.02	0.11	0.06	0	0.05	0.01	0.25	4
1987	3	5.33	2.73	0.97	0.85	0.9	0.16	0.63	11.57	5
1989	3	121.33	60.47	34.35	36.45	19.93	8.42	10.36	291.31	4
1995	1	64.35	25.86	3.92	1.94	0.9	0.27	0.14	97.38	0
1996	1	164.94	182.75	93.1	78.07	35.63	10.98	8.41	573.88	1
1999	1	0.84	3.86	2.93	1.99	1.00	0.44	1.33	12.39	11
2000	1	0.06	0.16	0.32	0.07	0.03	0.00	0.00	0.65	0
2001	1	0.79	1.00	0.14	0.39	0.35	0.00	0.00	2.67	0
2002	2	49.09	24.35	15.54	18.71	9.44	2.99	6.23	126.35	5
2003	1	156.83	157.19	88.03	77.7	38.77	15.26	12.54	546.32	2
2006	1	39.25	82.33	67.53	59.1	22.81	6.91	3.51	281.45	1
2007	1	2.19	4.99	6.12	12.49	7.38	4.74	11.34	49.25	23
Totals	17	605.01	545.72	313.06	287.82	137.14	50.22	54.5	1993.47	3
% of total area		30	27	16	14	7	3	3	100	3

of 229 yr (the time required to burn an area equivalent to the total area of YPMC forest), which is about 10 times longer than the expected value under a natural YPMC fire regime (22 yr to 30 yr; Mallek *et al.* 2013). There was no temporal trend in forest burned area ($P = 0.125$, R^2(adj) = 0.066; Table 2, Figure 2), and there were no significant autoregressive effects of year. The year with the most area burned in the forest types analyzed were, in descending order, 1996, 2003, 1989, and 2006. In these years, 1692 ha burned, or 85 % of the total.

All of the fires we identified started outside the park or in chaparral or herbaceous vegetation in the park's lower southern region, and most entered YPMC forest areas under relatively severe fire weather conditions (G. de León Girón, National Commission of Natural Protected Areas, Sierra San Pedro Mártir National Park, Ensenada, Baja California, Mexico, and J.C. Dominguez, CONAFOR, Mexicali, Mexico, personal communications). All lightning ignitions that occurred in Jeffrey pine or mixed conifer forest in the park between 1984 and 2010 (an average of 7 to 15 per year) were suppressed before they reached more than a few hectares in size, and they were not included in our analysis because they left no signal in the LANDSAT imagery. Most of the fires within the park occurred in its southern third, where the western (windward) escarpment is lower and drier than in the north of the park. The landscape in this southern area is dominated by chaparral and rock outcrops with little forest on its western side, whereas in the central and southeastern portions forest is distributed mostly around the fringes of large meadows and in topographic concavities with less exposure to the sun, at altitudes of around 2000 m to 2100 m. Large expanses of forest are mostly found in the higher northern part of the park. In this area, we identified and digitized three fires that

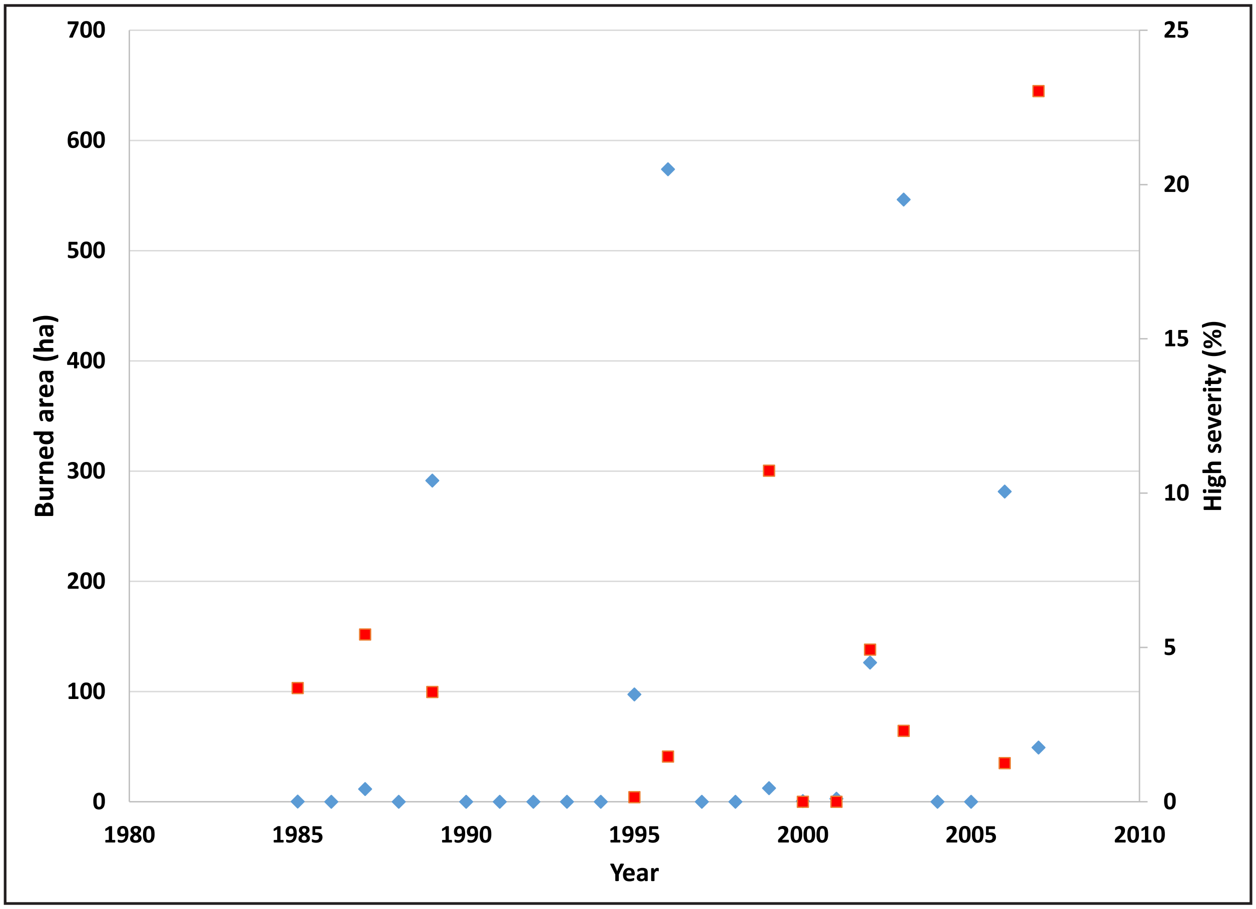

Figure 2. Annual values for burned area and percent high severity fire in Jeffrey pine and mixed conifer forests, Sierra de San Pedro Mártir National Park, 1984 to 2010. Blue diamonds represent burned area (ha) and the red squares represent high severity (%).

started outside the park as a result of human activities. All three fires occurred under windy, dry conditions, and burned principally chaparral vegetation.

Patterns and Trends in High Severity Fire from 1984 to 2010

Almost all of the high severity fire (≥90% BA change) burned in chaparral vegetation (Figure 3). This sort of fire effect is expected for this type of vegetation (Sugihara *et al.* 2006). The years with the most high severity fire area were, in descending order, 2003, 1986, 1989, and 2006 (Figure 4).

Over the time series, fires in Jeffrey pine and mixed conifer forests burned an average of 3% of their area at high severity (Figure 5). Both forest types were dominated by unchanged and low severity fire (≥0% to <25% change = 74% of burned area in Jeffrey pine and 70% in mixed conifer). The current high severity fire rotation period—the time required for stand replacing fire to occur across an area equivalent to the area of YPMC forest in the park—is about 7650 yr. This is more than 7.5 times longer than the expected high severity rotation with 3% high severity under a natural YPMC fire frequency (22 yr to 30 yr overall fire rotation period; Mallek *et al.* 2013).

There was no trend in fire severity over time ($P = 0.857$, $R^2(adj) = 0$; Table 2, Figure 2), and there were no significant autoregressive effects of year. The year with the highest percentages of high severity fire were 2007, 1987, and 1999 (Figure 2).

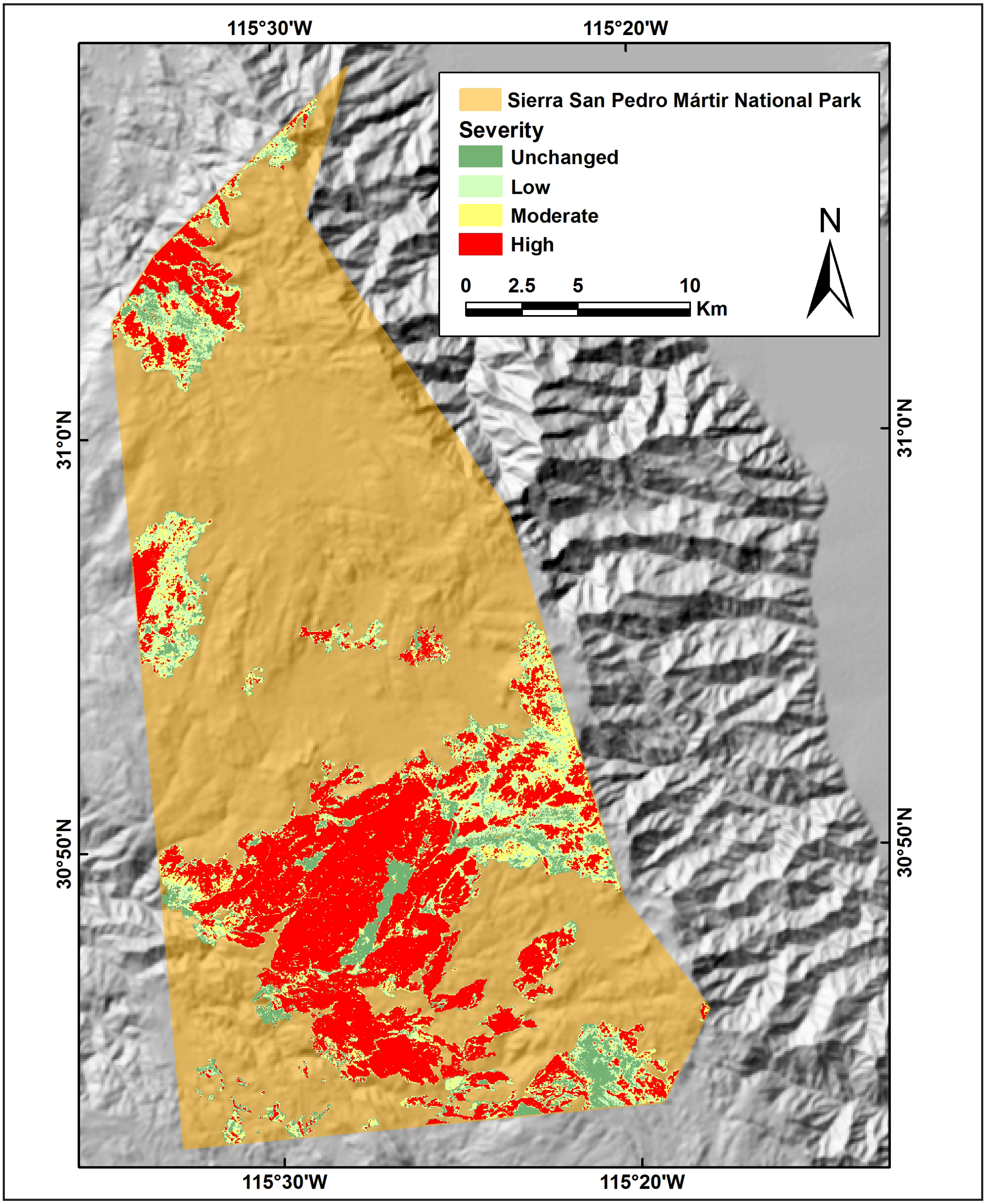

Figure 3. Fire severity map for 32 fires occurring within the boundaries of Sierra de San Pedro Mártir National Park, 1984 to 2010. Fire severity is based on BA change. Within the fire polygons, darker green represent unchanged (0% change), light green represents low severity fire (>0% to <25% change), yellow represents moderate severity fire (≥25% to <90% change), and red represents high severity fire (≥90% change). Almost all high severity fire occurred in chaparral vegetation.

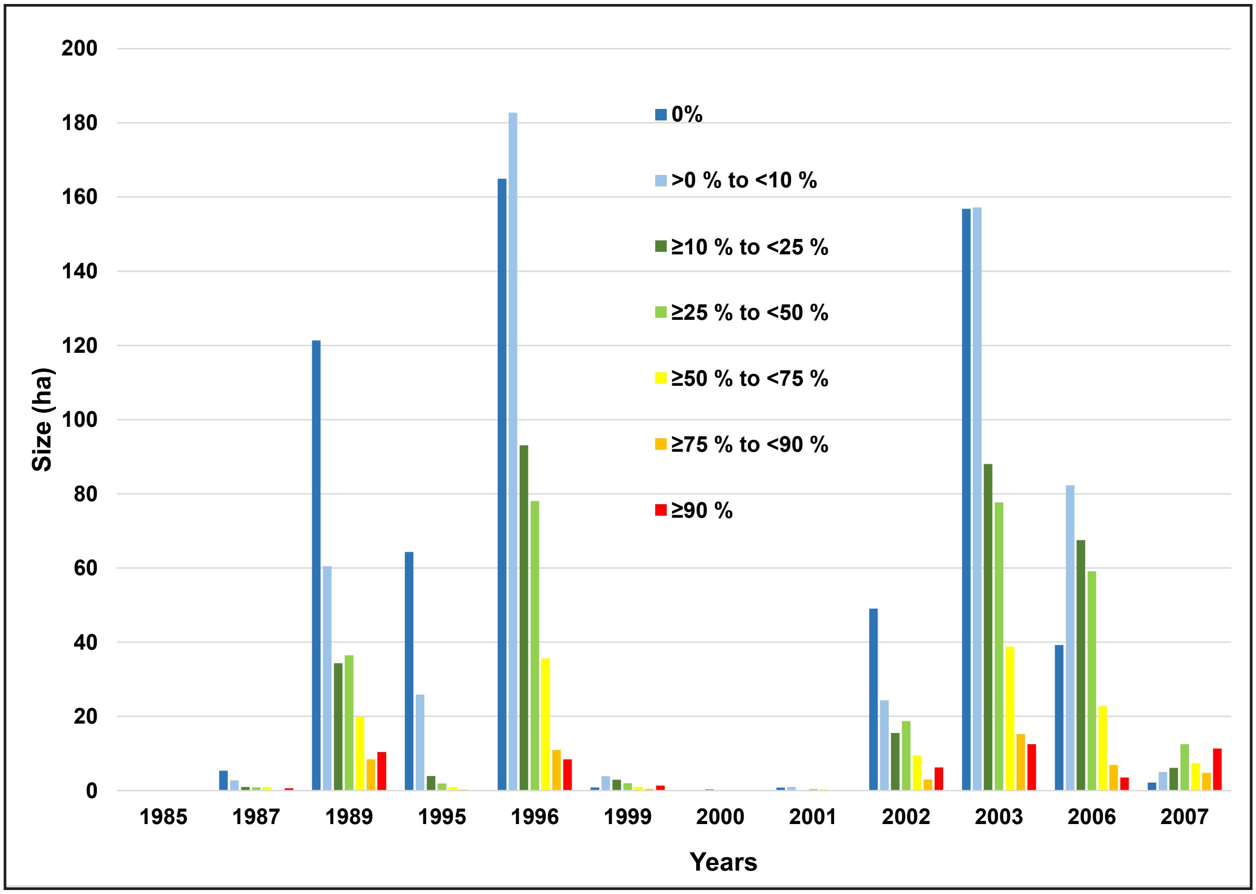

Figure 4. Area burned in Jeffrey pine and mixed conifer forests in the Sierra de San Pedro Mártir National Park, Mexico, from 1984 to 2010, classified by basal area mortality class and portrayed by year.

The distribution of high fire severity in the SSPMNP since 1984 (3 %) was much lower than that in the Sierra Nevada (33 %) over the same period (Figure 6).

High Severity Patch Size

The average size of high severity patches within forest fires in the SSPMNP increased between 1984 and 2010 (P = 0.018, R^2(adj) = 0.426; Table 2, Figure 7); there were no significant autoregressive effects. The overall average patch size was 2.86 ha (± 0.97 SE), the median was 0.63 ha. The smallest patch we measured was 0.009 ha (1985), the largest was 11.3 ha (2007).

In summary, we found that (1) forest fires in Jeffrey pine and mixed conifer forests in the Sierra de San Pedro Mártir National Park currently burn an average of about 3 % of their area at high (stand replacing) severity; (2) there is no current temporal trend in either burned area or percent high severity; (3) high severity patch sizes are small but increasing in size; and (4) fire frequencies in YPMC forest are being severely constrained by fire suppression tactics in the SSPMNP.

DISCUSSION

The percentage of YPMC forest area burning at high severity in the SSPMNP is very low. This is remarkable considering that the fires that we analyzed were almost entirely large, wind-driven events that began in chaparral below the forested part of the park and entered the forest moving rapidly under severe fire weather conditions. In the SSPMNP, when

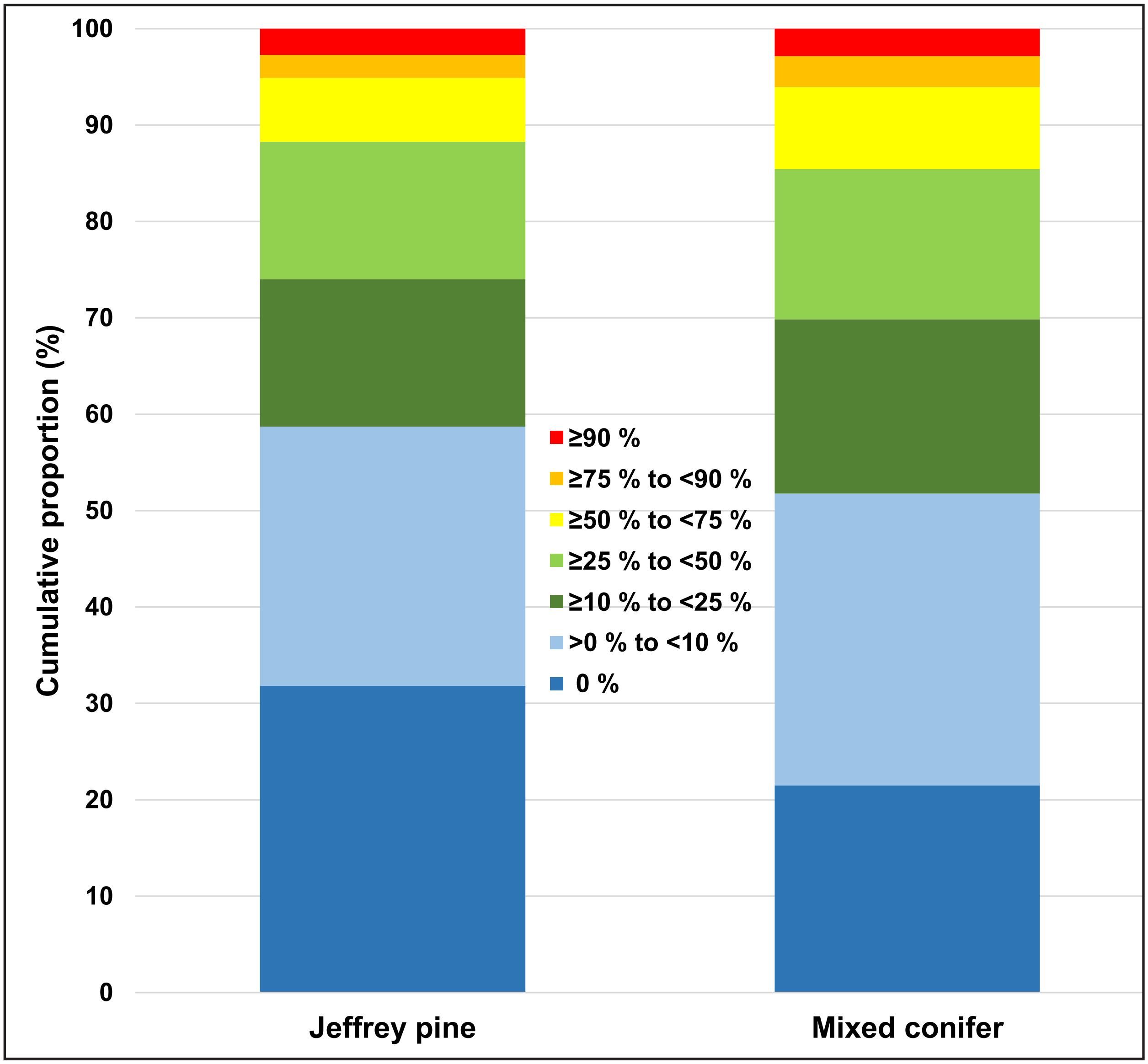

Figure 5. Summary of basal area mortality classes for the period 1984 to 2010, in Jeffrey pine and mixed conifer forests, Sierra de San Pedro Mártir National Park, Mexico.

such fires reach the forest edge they are crown fires, but they usually rapidly drop to the surface in the absence of sufficient surface fuels and crown connectivity, and they can usually be put out within a few hundred meters of the forest edge (G. de León Girón, personal communication). This sort of behavior is reminiscent of the behavior of wildfires in Alta California that encounter forest thinning treatments that have markedly reduced surface and ladder fuels, and a transition from crown fire to surface fire generally occurs within 100 m of the treatment boundary (Safford *et al*. 2012). In contrast, most areas of YPMC forest in Alta California outside of the national parks have not experienced a single fuel reducing event in the form of a low to moderate severity fire or a fuels treatment for a century or more (North *et al*. 2012, Safford and Van de Water 2014, Steel *et al*. 2015). As a result, the entrance of fast moving chaparral-fueled fires into conifer stands in Alta California usually engenders large area of forest mortality. Examples of this dynamic just north of the border

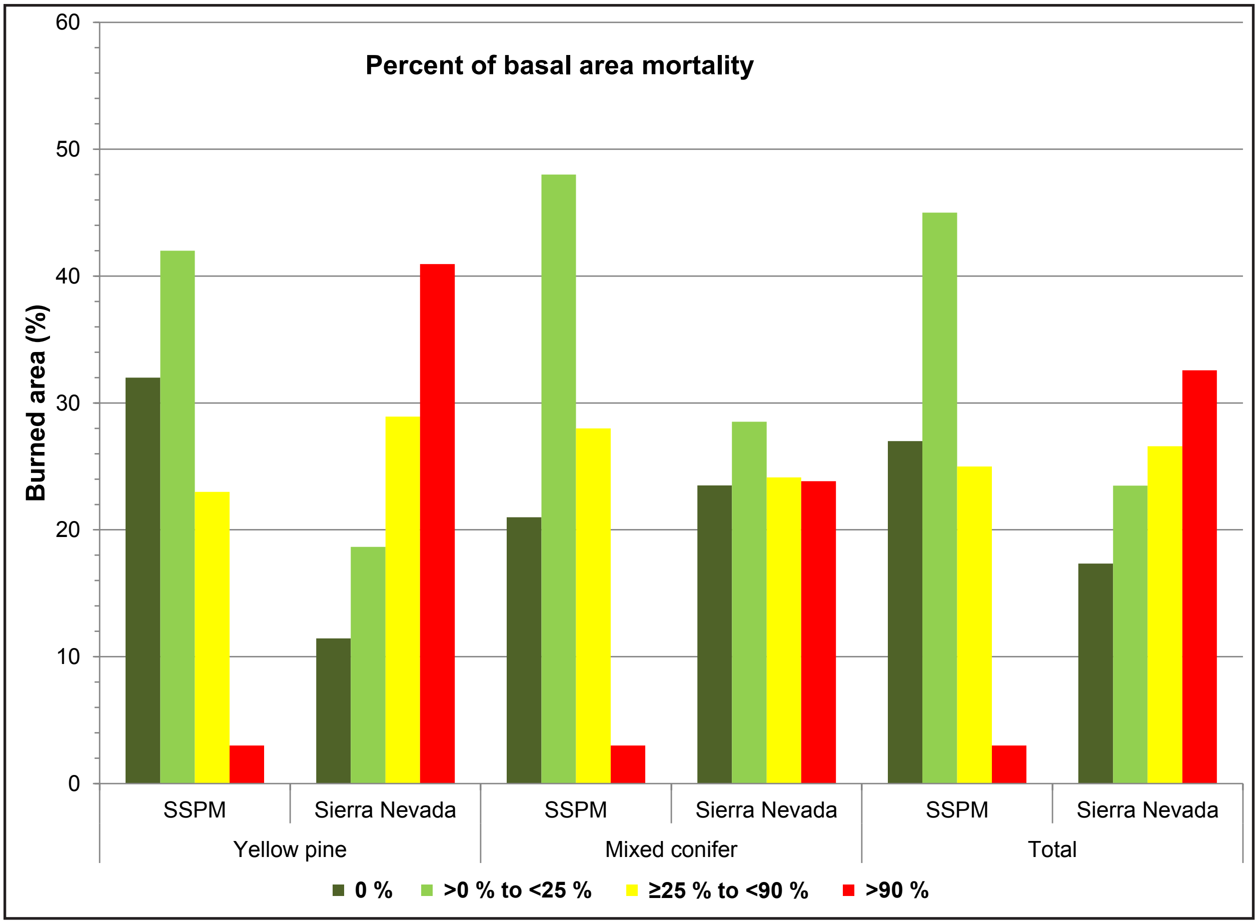

Figure 6. Comparison between mean fire severity distributions in the Sierra de San Pedro Mártir National Park, Mexico, and the Sierra Nevada of Alta California for 1984 to 2010. Sierra Nevada data from J.D. Miller, USDA Forest Service, McClellan, California, unpublished data. Darker green represent unchanged (0 % change), light green represents low severity fire (>0 % to <25 % change), yellow represents moderate severity fire (≥25 % to <90 % change), and red represents high severity fire (≥90 % change)

include the 2003 Cedar Fire in the Cuyamaca Mountains and Laguna Mountains near San Diego, and the 2013 Mountain Fire in the San Jacinto Mountains, at the northern end of the Peninsular Range.

Contemporary fires in the SSPMNP burn at much lower severity than similar YPMC forests in Alta California that have experienced 70 yr to 100 yr of fire suppression and selective logging of the fire tolerant species. Indeed, the contemporary percentage of high severity fire in the SSPMNP is more than 10 times lower than in US Forest Service managed YPMC forests in the Sierra Nevada over the same 1984 to 2010 period (Figure 6; Miller and Safford 2012; J.D. Miller, USDA Forest Service, McClellan Park, California, USA, unpublished data). The severity of fires in the SSPMNP is similar however to the historical (pre-Euro-American settlement) values reported for Alta California YPMC forests (Mallek *et al*. 2013, Safford and Stevens 2016). Mallek *et al*. (2013) summarized historical accounts, contemporary reference data, and models and concluded that, before Euro-American settlement, fires in yellow pine and mixed conifer forests burned on average about 5 % of their area at high (stand-replacing) severity. Leiberg (1902) found that about 8 % of the fire areas he inspected around the end of the nine-

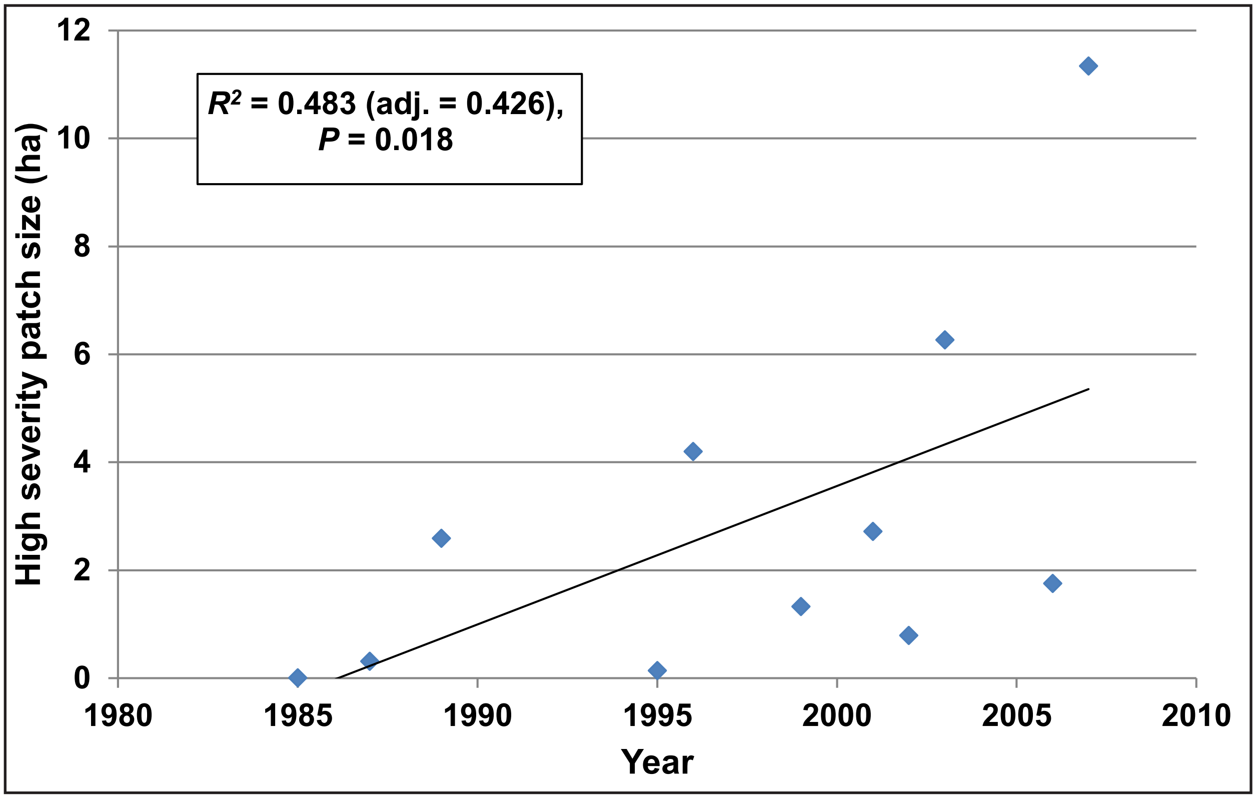

Figure 7. Annual means and trend in high severity patch size for Jeffrey pine and mixed conifer forest fires from 1984 to 2010, Sierra de San Pedro Mártir National Park, Mexico.

teenth century in the northern Sierra Nevada had burned at stand-replacing severity, and Show and Kotok (1925) estimated that about 5% of the typical area burned in the "California pine region" at the beginning of the twentieth century did so at high severity.

Except in a few national parks, Alta California forests have been under fire suppression management for about a century. Steel *et al*. (2015) estimated that almost 75% of yellow pine and mixed conifer forests under Forest Service management in Alta California had gone over a century without experiencing a fire after centuries to millennia with very frequent fire (5 to 10 fires in the average century according to Van de Water and Safford 2011). Barbour *et al*. (1993) estimated that half of the YPMC forest in Alta California had been logged at least once. Where clearcutting was not practiced, logging practices focused heavily on the largest yellow and sugar pines (and at lower elevations, Douglas-fir [*Pseudotsuga menziesii*]), greatly reducing the most fire tolerant individuals in the mixed conifer forest. Together, logging and fire exclusion have led to infilling by younger cohorts of shade tolerant but fire intolerant species like white fir and incense cedar, and great increases in surface and ladder fuels (Safford and Stevens 2016). Such changes in ecosystem processes, forest structure, and composition have transformed YPMC forests in Alta California from a system characterized by very frequent, mostly low severity fire, to one characterized by very infrequent fire with a notable high severity component. Together, Miller *et al*. (2009*b*), Miller and Safford (2012), Mallek *et al*. (2013), Steel *et al*. (2015), and Safford and Stevens (2016) demonstrate significant increasing trends in the proportion of fire area burning at high severity in YPMC forests managed by the Forest Service in the Sierra Nevada, as well as in the area of high severity fire itself. They also show that the average proportion of high severity fire occurring in modern (since 1984) YPMC forests in the Sierra Nevada is at least 5 to 6 times greater than under pre-Euro-American settlement conditions.

Unlike in the Sierra Nevada of Alta California, there is no temporal trend in either burned area or high severity fire in the SSPMNP, and fires continue to burn mostly at low severity (<25 % change). Differences in the average distribution of fire severities in forest burning in the SSPMNP since 1984 are in stark contrast to the distribution of fire severities in the Sierra Nevada of Alta California (Figure 6). We take the absence of a temporal trend, and the very low values of fire severity in modern forests, to indicate that the YPMC forests in the SSPMNP continue to function largely as they did before Euro-American settlement in California (but see below). These forests have been used as references forests for years, and many publications summarize forest structure data from the SSPMNP in order that they may be used to guide management prescriptions in places like the Sierra Nevada and southern California (Minnich *et al*. 2000, Stephens and Fulé 2005, Stephens and Gill 2005, Stephens *et al*. 2008, Dunbar-Irwin and Safford 2016).

In the SSPMNP data, there was no correlation between the year of greatest burned area and percentage or area of high severity fire. This is different than the Sierra Nevada, where there is a distinct positive correlation between fire size and percentage high severity (Miller *et al*. 2009*b*). We interpret this to mean that differences in fuels in the SSPMNP are more important than weather conditions to fire behavior. This is another indication that forests in the SSPMNP are much closer to historic reference conditions than YPMC forests in Alta California, because undegraded YPMC forest is perhaps the classic example of the fuel-limited forest fire regime (Mallek *et al*. 2013, Steel *et al*. 2015). The YPMC forests in Alta California have transitioned to systems in which the fire regime is much more driven by weather and climate as they have densified and filled with fuel and fire intolerant species (Safford and Stevens 2016).

Our finding that high severity patch size is increasing in the SSPMNP is disquieting, and it is in line with another recent comparative study between the SSPMNP and Alta California sites, which found that fuel loadings in the SSPMNP are nearing or even surpassing levels measured in forests on the east side of the Sierra Nevada (Dunbar-Irwin and Safford 2016). Together, these results suggest that 30 yr of fire suppression in the SSPMNP have begun to change the forest ecosystem and its fire regime. These changes have not yet manifested themselves in an increase in overall fire severity, but based on the experience of Alta California, it may not be long before they do. In June 2015, a wildfire in the Sierra Juarez (100 km north of the SSPMNP) burned 25 000 ha of chaparral and forest, including parts of the Constitution of 1857 National Park, and exhibited extreme fire behavior. It was one of the largest fires in memory in northern Baja California. North of the border, the Lake Fire in the San Bernardino National Forest (about 350 km north of the SSPMNP) burned 13 000 ha of YPMC and upper montane forest in June and July of 2015. The Mountain Fire burned 11 000 ha of YPMC forest and chaparral in the San Jacinto National Forest (300 km north of the SSPMNP) in July 2013. Forests in the SSPMNP have not experienced a fire of >300 ha since 2003, but fuels continue to accumulate in the park, and conditions for a severe forest fire improve with each passing year and with each lightning-ignited fire that is extinguished (82 % of fires in the SSPMNP are lightning ignited, and all of these are suppressed; J.C. Dominguez, personal communication). As noted by Dunbar-Irwin and Safford (2016), some recent fires in Alta California have burned areas larger than the entire forested area of the Sierra de San Pedro Mártir

National Park in only one or two days. Continued disregard for the long-term implications of strict fire exclusion and mounting forest fuels in the SSPMNP will likely result in large areas of forest loss in the future, especially as climates continue to warm and droughts become more profound.

Although we did not find autoregressive annual effects in our regression models, the most extensive burning in the SSPMNP occurred in fire seasons preceded by drier than average periods. In 1989, 1999, and 2006, the previous 12 months brought between 62 % and 69 % of the long-term average in precipitation. An average precipitation year occurred before 2003 (96 % of the long-term average), but the three previous years had experienced a record drought, such that the mean annual precipitation for the previous four years had been only 59 % of normal. Similarly, Skinner *et al*. (2008), in a tree ring analysis of the period 1700 through 1990 in the SSPMNP, concluded that periods of widespread fire were drier than normal, and wetter periods tended to experience few fires, although wet periods also positively influenced future fire activity at a 5-year lag, probably due to effects on litter quantity. Skinner *et al*. (2008) also found that the Pacific Decadal Oscillation and El Niño-Southern Oscillation interacted to influence shifts from high to low fire activity.

In conclusion, fires in the Sierra de San Pedro Mártir National Park continue to burn primarily at low severity, even after 30 yr of effective suppression of lightning-ignited fires. This is in stark contrast to similar forests in Alta California, which are experiencing fires of sizes and severities that fall far outside the historical range of variation. Forest structures and fire behavior in the SSPMNP are much nearer to the natural state of YPMC forest before Euro-American settlement than forests in Alta California, and hence the SSPMNP provides valuable reference information for managers in Alta California interested in restoring YPMC forests so as to be more resilient to fire and climate variability (Dunbar-Irwin and Safford 2016). Nonetheless, current fire suppression policies in Mexican national parks in Baja California are causing increases in forest fuels and are likely a major cause of recent increases in high severity patch size. Current wildfire trends in YPMC forests in Alta California should serve as a warning to Mexican managers that following the US down the fire exclusion path is likely to result in ecological disaster in these unique and important ecosystems.

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LITERATURE CITED

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Avery, T.E., and G.L. Berlin. 1992. Fundamentals of remote sensing and airphoto interpretation. Prentice Hall, Upper Saddle River, New Jersey, USA.

Barbour, M.G., B. Pavlik, F. Drysdale, and S. Lindstrom. 1993. California's changing landscapes: diversity and conservation of California vegetation. California Native Plant Society, Sacramento, California, USA.

Chander, G., B.L. Markham, D.L. Helder. 2009. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. ELSEVIER Remote Sensing of Environment 113: 893–903 doi: 10.1016/j.rse.2009.01.007

Delgadillo, J. 2004. El bosque de coníferas de la Sierra San Pedro Mártir, Baja California, Mexico. Instituto Nacional de Ecología, SEMARNAT, Distrito Federal, Mexico. [In Spanish.]

Dunbar-Irwin, M, and H.D. Safford. 2016. Climatic and structural comparison of yellow pine and mixed-conifer forests in northern Baja California (Mexico) and the eastern Sierra Nevada (California, USA). Forest Ecology and Management 363: 252–266. doi: 10.1016/j.foreco.2015.12.039

Fites-Kaufman J.A., P. Rundel, N. Stephenson, and D. Weixelman. 2007. Montane and subalpine vegetation of the Sierra Nevada and Cascade ranges. Pages 456–501 in: Barbour M.G., T. Keeler-Wolf, and A.A. Schoenherr, editors. Terrestrial vegetation of California. University of California Press, Berkeley, USA.

Eidenshink, J., B. Schwind, K. Brewer, Z.L. Zhu, B. Quayle, and S. Howard. 2007. A project for monitoring trends in burn severity. Fire Ecology 3(1): 3–21. doi: 10.4996/fireecology.0301003

Elvidge, C.D. 1990. Visible and near infrared reflectance characteristics of dry plant materials. International Journal of Remote Sensing 11: 1775−1795. doi: 10.1080/01431169008955129

Key, C.H. 2006. Ecological and sampling constraints on defining landscape fire severity. Fire Ecology 2(2): 178–203. doi: 10.4996/fireecology.0202034

Key, C.H., and N.C. Benson. 2006. Landscape assessment: remote sensing of severity, the Normalized Burn Ratio. Pages LA25–LA41 in: D.C. Lutes, editor. FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service General Technical Report RMRS-164, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Leiberg, J.B. 1902. Forest conditions in the northern Sierra Nevada, California. US Geological Survey Professional Paper 8, US Government Printing Office, Washington, D.C., USA.

Mallek, C., H. Safford, J. Viers, and J. Miller. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. Ecosphere 4(12): 153. doi: 10.1890/ES13-00217.1

Miller, J.D., and S.R. Yool. 2002. Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. Remote Sensing of Environment 82: 481−496. doi: 10.1016/S0034-4257(02)00071-8

Miller, J.D., and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment 109: 66−80. doi: 10.1016/j.rse.2006.12.006

Miller, J.D., E.E. Knapp, C.H. Key, C.N. Skinner, C.J. Isbell, R.M. Creasy, and J.W. Sherlock. 2009*a*. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment 113: 645–656. doi: 10.1016/j.rse.2008.11.009

Miller, J.D., and H.D. Safford. 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. Fire Ecology 8(3): 41–57. doi: 10.4996/fireecology.0803041

Miller, J.D., H.D. Safford, M.A. Crimmins, and A.E. Thode. 2009*b*. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12: 16–32. doi: 10.1007/s10021-008-9201-9

Miller, J.D., and B. Quayle. 2015. Calibration and validation of immediate post-fire satellite derived data to three severity metrics. Fire Ecology 11(2): 12–30.

Minnich, R.A., M.G. Barbour, J.H. Burk, and J. Sosa-Ramirez. 2000. California mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27: 105–129. doi: 10.1046/j.1365-2699.2000.00368.x

Minnich, R.A., F. Franco-Vizcaino, J. Sosa-Ramirez, and C. Yue-Hong. 1993. Lightning detection rates and wildland fire in the mountains of northern Baja California, Mexico. Atmostera 6: 235–253.

Murphy, K L., J.M. Klopatek, and C.C. Klopatek. 1998. The effects of litter quality and climate on decomposition along an elevational gradient. Ecological Applications 8: 1061–1071. doi: 10.1890/1051-0761(1998)008[1061:TEOLQA]2.0.CO;2

North, M., B.M. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry 110: 392–401. doi: 10.5849/jof.12-021

Safford, H.D., and J.T. Stevens. 2016. Natural Range of Variation (NRV) for yellow pine and mixed conifer forests in the Sierra Nevada, southern Cascades, and Modoc and Inyo national forests, California, USA. USDA Forest Service General Technical Report PSW-GTR-in press, Pacific Southwest Research Station, Albany, California, USA.

Safford, H.D., J.T. Stevens, K. Merriam, M.D. Meyer, and A.M. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. Forest Ecology and Management 274: 17–28. doi: 10.1016/j.foreco.2012.02.013

Safford, H.D., and K.M. Van de Water. 2014. Using Fire Return Interval Departure (FRID) analysis to map spatial and temporal changes in fire frequency on national forest lands in California. USDA Forest Service Research Paper PSW-RP-266, Pacific Southwest Research Station, Albany, California, USA.

Shlisky, A., J. Waugh, P. Gonzalez, M. Gonzalez, M. Manta, H. Santoso, E. Alvarado, A. Ainuddin Nuruddin, D.A. Rodríguez-Trejo, R. Swaty, D. Schimidt, M. Kaufmann, R. Myers, A. Alencar, F. Kearns, D. Johnson, J. Smith, and D. Zollner. 2007. Fire, ecosystems and people: threats and strategies for global biodiversity conservation. The Nature Conservancy Global Fire Initiative Technical Report 2007-2, The Nature Conservancy, Arlington, Virginia, USA.

Show, S.B., and E.I. Kotok. 1925. Fire and the forest (California pine region). US Department of Agriculture Circular 358, Washington, D.C., USA.

Shumway, R.H. 1988. Applied statistical times series analysis. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Singh, A. 1989. Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing 10: 989−1003. doi: 10.1080/01431168908903939

Skinner C.N., J.H. Burk, M.G. Barbour, F. Franco-Vizcaino, and S.L. Stephens. 2008. Influences of climate on fire regimes in montane forest of north-western Mexico. Journal of Biogeography 35: 1436–1451. doi: 10.1111/j.1365-2699.2008.01893.x

Steel, Z.L., H.D. Safford, and J.H. Viers. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6(1): Article 8.

Stephens, S.L., D.L. Fry, and E. Franco-Vizcaíno. 2008. Wildfire and spatial patterns in forests in northwestern Mexico: the United States wishes it had similar fire problems. Ecology and Society 13(2):10.

Stephens, S.L., and P.Z. Fulé. 2005. Western pine forests with continuing frequent fire regimes: possible reference sites for management. Journal of Forestry 103: 357–362.

Stephens, S.L., and S.J. Gill. 2005. Forest structure and mortality in an old-growth Jeffrey pine-mixed conifer forest in north-western Mexico. Forest Ecology and Management 205: 15–28. doi: 10.1016/j.foreco.2004.10.003

Stephens, S.L., J.M. Lydersen, B.M Collins., D.L. Fry, and M.D. Meyer. 2015. Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the southern Sierra Nevada. Ecosphere 6(5): 79. doi: 10.1890/ES14-00379.1

Stephens, S.L., and L.W. Ruth. 2005. Federal forest-fire policy in the United States. Ecological Applications 15: 532–542. doi: 10.1890/04-0545

Stephens, S.L., C.N. Skinner, and S. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forest in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 33: 1090–1101. doi: 10.1139/x03-031

Sugihara, N.G., J.W. van Wagtendonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode, editors. 2006. Fire in California's ecosystems. University of California Press, Berkeley, USA. doi: 10.1525/california/9780520246058.001.0001

Trejo, D.A.R. 2008. Fire regimes, fire ecology, and fire management in Mexico. AMBIO 37(7): 548–556. doi: 10.1579/0044-7447-37.7.548

van Wagtendonk, J.W., and J. Fites-Kaufman. 2006. Sierra Nevada Bioregion. Pages 264–294 in: N.G. Sugihara, J.W. van Wagtendonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode, editors. Fire in California's ecosystems. University of California Press, Berkeley, USA. doi: 10.1525/california/9780520246058.003.0012

Van de Water, K., and H. Safford. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecology 7(3): 26–58. doi: 10.4996/fireecology.0703026