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# Early impacts of fire suppression in Jeffrey pine – Mixed conifer forests in the Sierra San Pedro Martir, Mexico

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ABSTRACT

Fire exclusion was first implemented across large areas of California and other areas of western North America in the late 19th or early 20th centuries but few studies have investigated how forests in the early decades after this decision were impacted. Jeffrey pine-mixed conifer forests of northern Baja California, Mexico, offer an area where this can be examined since fire suppression did not begin until the early 1970's. We use repeated forest and fuel measurements taken over a 25-year period (1998–2023) and found significant changes in forest structure and fuel loads (increased tree density, fine fuel loads, large fuel loads, snag density, snag basal area) that together clearly demonstrate the cumulative effects of fire removal. Interestingly, Jeffrey pine became more dominant despite the lack of recent fire, which is counter to the shift towards more shade-tolerant tree species observed in many other fire-suppressed, frequent-fire forests in the western US. Although these changes in Baja California forests point towards increased fire hazard, they are still in relatively low hazard conditions compared to long-fire suppressed forests in the western US. Prescribed fire or managed wildfire could easily be applied to counter the increased fuel loads and tree densities detected in this work, without the need for mechanical manipulation. In addition to maintaining resilient forests, using fire will reduce the risk of losing the large astronomical observatory at this site to wildfire. Restoration and stewardship of resilient forest structures similar to those in Baja California is the only way forward to conserve similar forests of the Sierra Nevada, southern California mountains, and elsewhere in the western US.

## 1. Introduction

Fire is a critical process in many forests of North America. For thousands of years ignitions from lighting and Indigenous people have shaped these forests by reducing fuel loads, recycling nutrients, creating snags and downed wood, and for producing food, cordage, medicine, and other materials for the Indigenous people who inhabit these areas (Lewis and Ferguson, 1988; Stewart, 2002; van Wagtendonk et al., 2018; Pyne, 2019; Anderson, 2005).

Fire exclusion was first implemented across vast areas of western North America staring in the late 19th or early 20th centuries (Swetnam (1993); Van Horne and Fulé (2006); Beaty and Taylor, 2008; Brown et al., 2008; Skinner et al., 2008; Daniels et al., 2017; Heyerdahl et al., 2019). The removal of fire has changed frequent-fire forests profoundly by increasing fuel loads and shade tolerant tree regeneration, and this has increased their vulnerability to large, high severity wildfires (McIver and Starr, 2001; Brown et al., 2004; Hagmann et al., 2021). When fire suppression was combined with the harvesting of large trees early in the 20th century, a niche was opened for rapid regeneration and establishment of more shade-tolerant species, altering the structure of these formerly fire-adapted forests (Knapp et al., 2013; Collins et al., 2017).

Early forest researchers anticipated that the removal of fire from frequent-fire forests in California would increase their fuel loads. Show and Kotok (1924) wrote "That maximum protection or fire exclusion inevitably increases hazard by the encouragement of undergrowth is, of course, true, but such added hazard in no way vitiates the reasons for protection". While fire suppression began to impact frequent-fire forests at the end of the 19th or beginning of the 20th centuries the earliest studies documenting changes in western North America forests did not occur until the first quarter to mid-20th century (Leopold, 1924;

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Weaver, 1947; Biswell, 1958). An increase in the number of papers further documenting forest changes resulting from fire suppression were published in the 1970's (Kilgore, 1973; Kilgore and Sando, 1975; Agee et al., 1976; Parsons, 1978; Parsons and DeBenedetti, 1979) but these were written approximately 100-years after the removal of fire. Using repeated measurements from plot networks allows investigations of longer-term changes in forest structure from fire suppression, harvesting, and climate change, but such sites are relatively rare (Cleavitt et al., 2018; Crampe et al., 2021; May et al., 2023) because of the complexity of maintaining and funding such operations.

The conifer forests of northern Baja California, Mexico (Fig. 1A), offer an area where the early effects of fire suppression can be investigated. These forests occur in the Sierra San Pedro Martir (SSPM) and are relatively unique in that harvesting has never occurred and limited fire suppression only began in the 1970's (Stephens et al., 2003; Skinner et al., 2008), although the removal of Indigenous burning began much earlier (Evett et al., 2007). Although previous research has documented their high forest resilience (Stephens et al., 2008; Rivera-Huerta et al., 2016; Murphy et al., 2021) the approximately 50-years of fire suppression may be increasing fire hazards in these forests (Dunbar-Irwin and Safford, 2016) by increasing fuel loads and small tree densities.

We used repeated forest and fuel measurements taken over a 25-year period (1998–2023) in the SSPM to examine the following questions 1) Have fuel loads changed including litter, fine-woody, and large fuels? 2) Has forest density changed and if so, are their differences in the responses of different species? and 3) Has snag abundance changed over this 25-year period? This information could be of interest to forest managers in northwest Mexico and scientists and managers interested in frequent-fire adapted forests throughout North American and elsewhere.

## 2. Materials and methods

### 2.1. Study design and location

The study was conducted in the SSPM National Park in northern Baja California, Mexico. The region has a Mediterranean climate and shares similar vegetation communities and historic fire regimes with the eastern Sierra Nevada, Lake Tahoe basin, and the mountains of southern California (Minnich et al., 1995; Barbour et al., 2002; Dunbar-Irwin and Safford, 2016). Median fire return intervals in Jeffrey pine–mixed conifer forests in the SSPM are shorter than 15-years at all composite scales (Stephens et al., 2003), and this is comparable to past fire frequency in similar forests of the eastern Sierra Nevada (Dunbar-Irwin and Safford, 2016). The seasonality of past fires in the SSPM differs from that in California with the majority of fires recorded in the earlywood portion of annual ring before the summer rains , most fires in Californian forests are recorded in the latewood or dormant periods (Stephens et al., 2003).

Average annual precipitation in the upper plateau of the SSPM was 55 cm from a temporary set of weather stations installed from 1989 to 1992 (Minnich et al., 2000). The soils of the SSPM are unclassified but those in the study area are Entisols (Stephens and Gill, 2005). Soils are shallow, well to excessively drained, and relatively acidic. The most common soil texture is loamy sand; parent material is diorite. Soil chemistry and texture from the study area are typical of granite-derived soils in similar forests in the eastern Sierra Nevada (Potter, 1998). The SSPM has experienced livestock grazing at varying intensities over the last 200-years (Minnich et al., 1997; Minnich and Franco, 1998). The number of livestock in the SSPM was described as "well up to the average mission herd" and in 1801 consisted of 700 cattle, 500 sheep, 150 goats, 50 swine, and 169 horses, mules, and donkeys (Meigs, 1935). In the mid-19th century, cattle numbers increased substantially in the region (Henderson, 1964).

A 7-by-7 plot grid (200-m spacing) was established in 1998 with similar topography (slopes 0–20 %, aspect west to southwest) and soils in Jeffrey pine-mixed conifer forests in the SSPM, located at latitude 31.01°, longitude 115.51°, between 2400 and 2500 m above sea level. Plot centers were marked with a steel stake and trees were tagged to help locate the plot. Dominant tree species in this area include Jeffrey pine, white fir (*Abies concolor*), and sugar pine (*Pinus lambertiana*), with minor amounts of lodgepole pine (*Pinus contorta*), quaking aspen (*Populus*

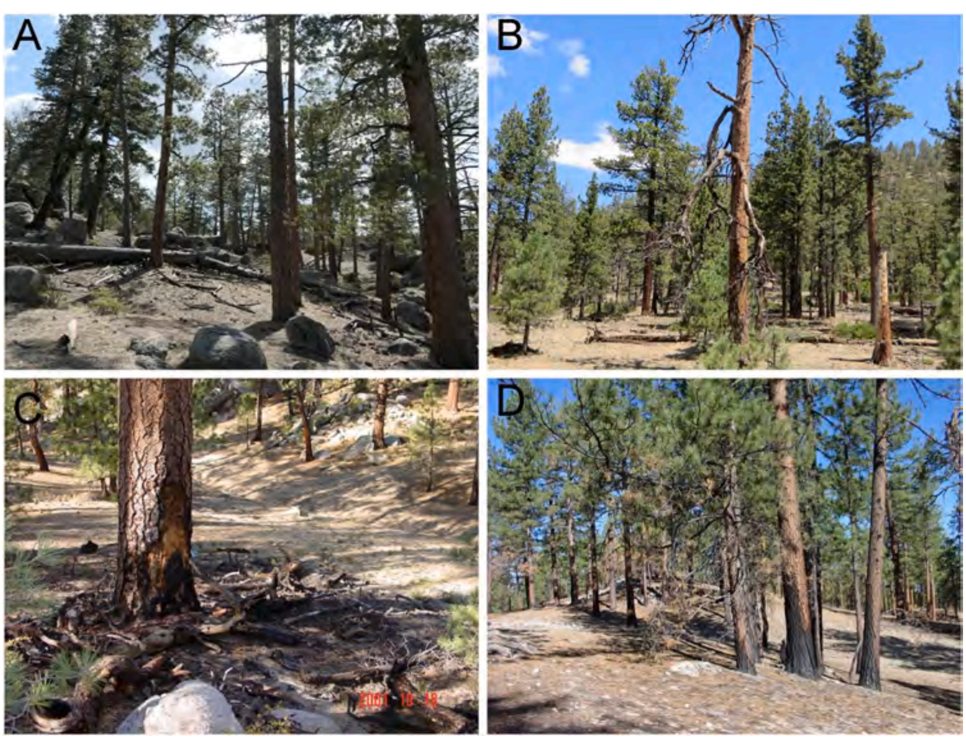


**Fig. 1.** Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir approximately 2 km west of the northern portion of Vallecitos Meadow A) in 2023, B) mortality of individual trees from the 1999–2002 drought, C) suppressed lightning ignited fire in 2001 within the 7 ×7 grid, and D) 2002 lightning fire within the grid that burned approximately 2 ha before being suppressed. Photos: Scott Stephens.

*tremuloides*), and incense-cedar (*Calocedrus decurrens*)(Stephens, 2004; Stephens and Gill, 2005).

### 2.2. Data collection

#### 2.2.1. Forest structure

All overstory trees (> 2.5 cm diameter at 1.37 m above ground level (DBH)) were surveyed in the 49 plots. DBH and species were recorded for each live tree within 0.1 ha circular plots; DBH, species, height, and snag condition class (Cline et al., 1980) were recorded for each snag (standing dead tree) within 0.4 ha circular plots using the same plot center. A larger snag plot was used because snags are relatively rare in the forests of the SPPM (Stephens, 2004, Stephens et al., 2007). All seedlings (height < 1.37 m or DBH < 2.5 cm) within each 0.1 ha plot were tallied by species and status (live or dead). Forest structure was measured in June/July of 1998, 2010, and 2023.

#### 2.2.2. Surface fuels

Surface fuels were sampled using the line intercept method (Brown, 1974). At each plot, three 13 m transects were installed from plot center in random azimuth directions. Along each transect, we recorded all woody debris with a diameter between 0 and 0.64 cm (1 hr fuels) and 0.64–2.5 cm (10 h fuels) from 0 to 3 m, with a diameter of 2.5–7.6 cm (100 h fuels) from 0 to 5 m, and all coarse woody debris with a diameter >7.6 cm (1000 h fuels) were measured for diameter and if they were sound or rotten along the full 13 m transect. Additionally, duff and litter depth (cm) was measured at 3 and 5 m on each transect. Data were averaged for each plot. Surface fuels were measured in June/July of 1998 and 2023.

### 2.3. Data analysis

All data analysis was performed in R. Descriptive statistics of forest structure—live tree density (trees ha$^{-1}$), snag density (snags ha$^{-1}$), seedling density (seedling ha$^{-1}$), tree basal area (m$^2$ ha$^{-1}$), and snag basal area (m$^2$ ha$^{-1}$)—were calculated for each of the three sampling years. Descriptive statistics of fuel loads were calculated for the 1998 and 2023 sampling years. Surface and ground fuel loads (Mg ha$^{-1}$) by size class (litter, 1 hr, 10 hr, 100 hr, and 1000 hr) were estimated from line-intercept transect data using the package Rfuels (Foster et al., 2018). These estimates were aggregated into fine woody debris (FWD: 1 hr, 10 hr, 100 hr) and coarse woody debris (CWD: 1000 hr). No duff was recorded during sampling.

Changes in tree basal area and fuel loads between sampling times were assessed with repeated measures one-way analysis of variance, and differences were considered significant when p-values resulting from Tukey's HSD post-hoc test was <0.05. We assessed count data (trees ha$^{-1}$, snags ha$^{-1}$, and seedling ha$^{-1}$) with a negative binomial generalized linear model (Agresti, 2012). For count analyses, we used the R package MASS (Venables and Ripley (2002)).

## 3. Results

### 3.1. Tree growth

We calculated the change in DBH for all individual trees between sampling years to quantify growth. Individual trees that were tracked for the duration of the study (trees were tagged sequentially within the plots) varied by species; the most common species being Jeffrey pine (n = 236), white fir (n = 81), sugar pine (n =31) and lodgepole pine (n = 11). We did not detect significant changes in median DBH for white fir, sugar pine, or lodgepole pine between sampling years. Median DBH for Jeffrey pine was 26 cm in 1998 and this increased to 28 cm in 2010 and to 31 cm in 2023. The change was marginally significant (p = 0.07) between 1998 and 2023 (Fig. 2).

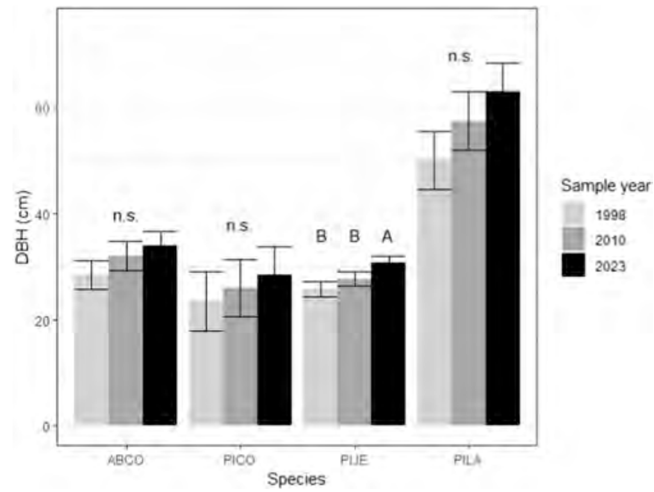


**Fig. 2.** Median DBH of ABCO (white fir– *Abies concolor*), PICO (lodgepole pine— *Pinus contorta*), PIJE (Jeffrey pine— *Pinus jeffreyi*), and PILA (sugar pine— *Pinus lambertiana*). Error bars represent 1 standard error. Significant differences in DBH were determined with a repeated measures one-way ANOVA analysis and Tukey's HSD post-hoc test. Labels of "n.s." represent species for which no difference was detected between sampling times; groups labeled "A" were detected to have significantly greater values than groups labeled "B". The change in Jeffrey pine DBH was marginally significant (p = 0.07) between 1998 and 2023.

### 3.2. Fuels

Fuel loads generally increased between the 1998 and 2023 sampling years except for 1 hr fuels that decreased (Table 1). Average litter load (Mg ha$^{-1}$) for the 49 plots increased by 3.7 Mg ha$^{-1}$, 10 hr fuels by 0.3 Mg ha$^{-1}$, and 100 hr fuels by 3.3 Mg ha$^{-1}$. One hr fuel load decreased by 0.4 Mg ha$^{-1}$, although overall load of fine woody debris (FWD) increased by 3.5 Mg ha$^{-1}$. Heavy downed woody (1000 hr) fuel load increased by 27.4 Mg ha$^{-1}$ and the total fuel load increased by approximately 35 Mg ha$^{-1}$ between 1998 and 2023.

### 3.3. Tree basal area

Plot-estimated overstory basal area increased over the study period from 18.5 (1998) to 18.6 (2010) to 21.6 (2023) m$^2$ ha$^{-1}$, although we did not detect a significant difference between years (Figs. 3A and 4).

### 3.4. Snag density and basal area

Mean snag density was highly variable between plots, ranging from 0 to 32.5 snags ha$^{-1}$ (coefficient of variation of 125, 103, and 86, for

**Table 1**
Sierra San Pedro Martir fuel loads (Mg ha$^{-1}$) calculated in each sampling year (n = 49 plots). We define fine woody debris (FWD) as fine fuels < 7.6 cm in diameter, and coarse woody debris (CWD) as fuels > 7.6 cm diameter and at least 1 m in length. Significant differences in fuel loads between sampling times were determined with a repeated measure one-way ANOVA analysis and Tukey's HSD post-hoc test. Stars represent statistically different fuel loads (p<0.05).

| Fuel type | 1998 Mean (SE) | 2023 mean (SE) |
|---|---|---|
| Litter | 8.3 (0.8) | 12.0 (0.8) * |
| 1 h | 0.1 (0.02) | 0.05 (0.01)* |
| 10 h | 0.8 (0.1) | 1.1 (0.1) |
| 100 h | 1.2 (0.2) | 4.5 (0.4) * |
| 1000 h | 14.8 (3.6) | 42.2 (5.2) * |
| FWD | 2.1 (0.3) | 5.6 (0.5) * |
| Total | 25.1 (3.8) | 59.8 (6.1) * |

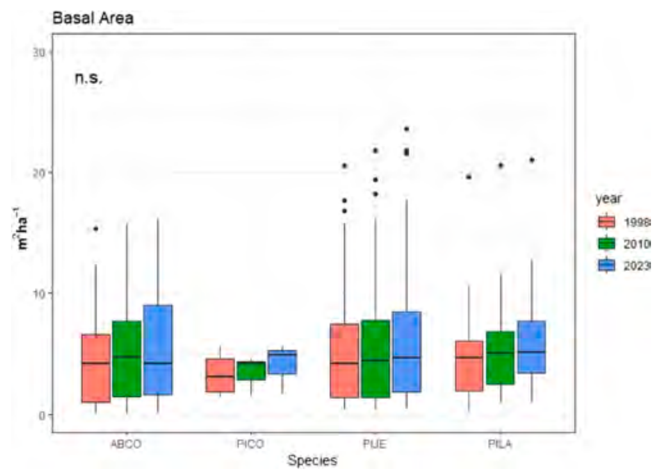


**Fig. 4.** Tree basal area by species from measurements taken in 1998, 2010, and 2023 in the Sierra San Pedro Martir. Significant differences between sampling times were tested with a repeated measures one-way ANOVA analysis and Tukey's HSD post-hoc test.

1998, 2010, and 2023, respectively). Median snag density increased over the study period from 2.5 (1998) to 3.75 (2010) to 5 (2023) snags ha$^{-1}$ (Fig. 3B), and the increase in snag density between 1998 and 2023 was statistically significant ($p < 0.05$). Snag basal area increased over the course of the study period from 0.8 m$^2$ ha$^{-1}$ in 1998 to 2.6 m$^2$ ha$^{-1}$ in 2023 ($p < 0.05$). By species, white fir snag basal area increased from 0.3 to 2.1 m$^2$ ha$^{-1}$ ($p < 0.05$), Jeffrey pine from 0.3 to 1.4 m$^2$ ha$^{-1}$ ($p < 0.05$), and sugar pine from 0.3 to 0.8 m$^2$ ha$^{-1}$ ($p = 0.55$). Density of lodgepole pine increased from 0.1 to 1.0, but this increase wasn't assessed statistically because in 1998, $n = 1$.

### 3.5. Seedling density

Seedling density ranged from 0 to 770 seedlings ha$^{-1}$. Median seedling density (seedlings ha$^{-1}$) was 100 in 1998, 140 in 2010, and 130 in 2023. We did not detect a significant difference in seedling density between sampling years (Fig. 3 C). We also observed the establishment of two species previously not measured within field plots in 2023, incense-cedar and quaking aspen.

### 3.6. Overstory tree density

Live overstory tree density increased over the study period (Fig. 3D). Median number of trees per hectare was 140 in 1998, 130 in 2010, and 190 in 2023, and we detected a significant increase from 2010 to 2023 ($p < 0.05$). This increase can be attributed to the ingrowth of Jeffrey pine, which is the only individual species for which an increase in tree density was statistically detected (Fig. 3E). Over the study period, Jeffrey pine density increased from 80 to 130 trees ha$^{-1}$.

## 4. Discussion

We detected significant changes in forest structure and fuel loads over the 25-year sampling period (increased tree density, fine fuel loads, large fuel loads, snag density, snag basal area) that together clearly demonstrate the cumulative effects of nearly 50-years of fire removal from these forests. The last large-scale fire that burned through the 49 plot grid was in 1946 with much smaller fires detected in the 1970's and 1980's (Stephens et al., 2003). We saw evidence of fire suppression including two lightning ignited fires suppressed within the 49 plot grid during our studies; a 2001 fire ignited a snag and was suppressed at approximately 100 m$^2$ in size (Fig. 1C) while a 2002 fire burned approximately 2 ha before it was contained with a handline (Fig. 1D). Both areas were easily accessible by off road vehicles or hiking allowing small hand crews to easily access and suppress these fires.

Similar fire management was performed in US forests early in the

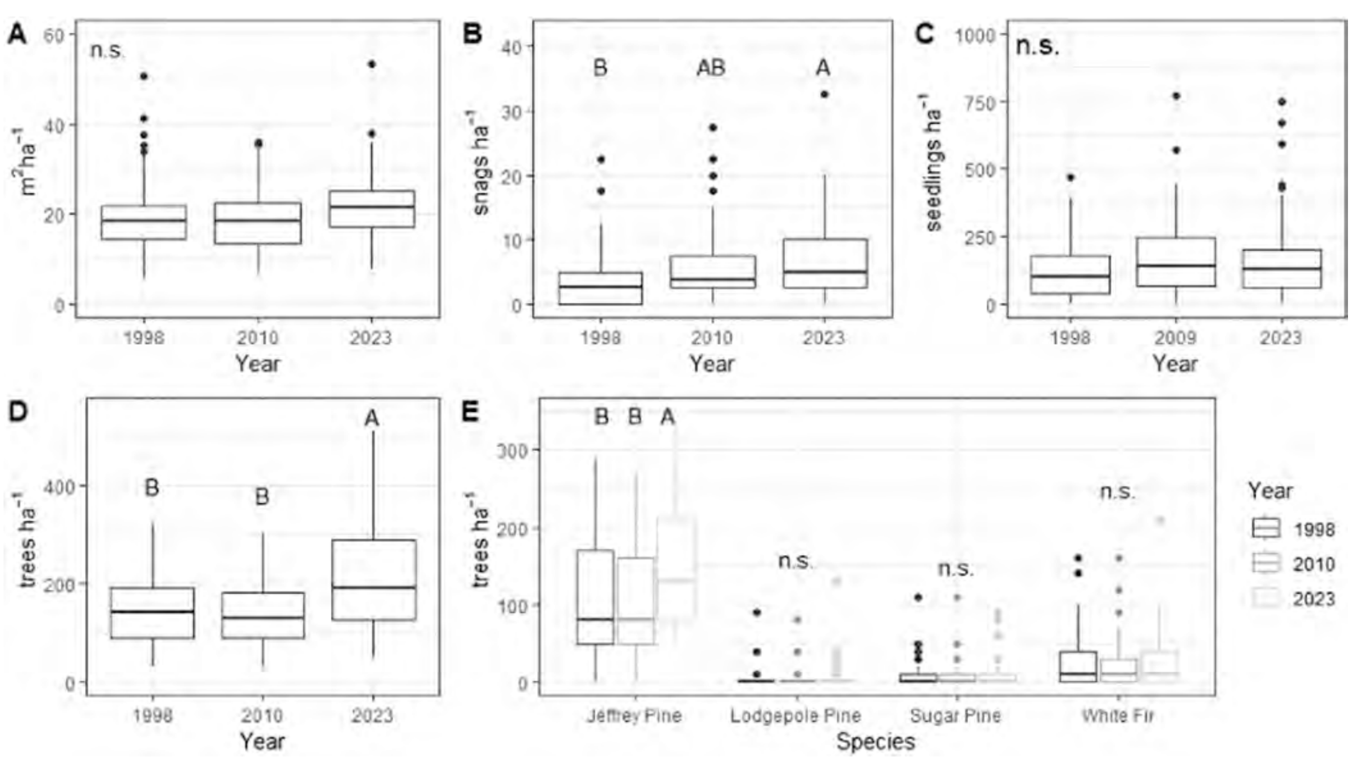


**Fig. 3.** (A) Tree basal area, (B) Snags per hectare, (C) Seedlings per hectare, (D) Trees per hectare, and (E) Trees per hectare by species. See Methods for information on the statistical tests. Groups labeled "A" were detected to have significantly greater values than groups labeled "B" ($p < 0.05$).

20th century when fire suppression was initiated (Pyne, 2019). During this early period fuel loads and forest density were low (similar to the SSPM today; Safford and Stevens, 2017) and this allowed small hand crews to easily suppress fires in most conditions. While photographs of early suppression activities are somewhat rare we can see the conditions of 'light burning' experiments in mixed-conifer forests in the northern Sierra Nevada in 1919 that show very low fuel loads burning with small flames (Fig. 5). Even under more severe weather conditions it would be difficult to produce large flame lengths resulting in most trees surviving these early fires, as is the case when fires burn in the SSPM today (Stephens et al., 2008; Murphy et al., 2021).

Forests in the SSPM are responding to climate change and fire suppression. Soil drying associated with anthropogenic climate change resulted in less than expected annual recruitment in the SSPM by the turn of the 21st century. Specifically, between 2000 and 2021, 1.2 fewer trees ha$^{-1}$ were predicted to have recruited due to climate change (Stephens et al., 2023a). However, recent fire suppression in the SSPM has resulted in 6 more seedlings ha$^{-1}$, which overrides the slight reduction in recruitment attributed to anthropogenic climate change (Stephens et al., 2023a). This increased tree recruitment, coupled with the observed increases in fine woody fuels, large wood, and snags, warrants continued monitoring, and active stewardship to reverse these trends. Interestingly, Jeffrey pine is becoming more dominant in this forest without any recent fire (Fig. 2 and 3), which is counter to the shift towards more shade-tolerant tree species observed in many other fire-suppressed, frequent-fire forests (Hagmann et al., 2021). Perhaps this is evidence of climate overriding expected successional changes in these marginally productive forests. We observed an increase in the mortality of large white firs during this study that were associated with high levels of fir mistletoe (*Phoradendron pauciflorum*) but this association needs further study.

Foresters and researchers who worked in conifer forests in the Sierra Nevada early in the 20th century believed that these forests were not adequately occupying available growing space for timber stating "California pine forests represent broken, patchy, understocked stands, worn down by the attrition of repeated light fires" (Show and Kotok, 1924). Show and Kotok (1924) believed if a policy of fire suppression was adapted this would increase tree densities and subsequently timber yields. This policy indeed increased tree densities throughout frequent-fire forests across the western US (Minnich et al., 1995; Hessburg et al., 2000; Allen et al., 2002; Brown et al., 2008; Hagmann et al., 2014; Stephens et al., 2015; Safford and Stevens, 2017; Collins et al., 2021). However, recent analyses of mixed-conifer forests in the northern, central and southern Sierra Nevada revealed current forests are considerably over stocked and vulnerable to wide-spread drought and bark beetle mortality whereas these forests in 1911 were in a very low competitive environment with high resilience (North et al., 2022; Stephens et al., 2023b).


**Fig. 5.** Photograph of early (1919) experimental prescribed burning in the northern Sierra Nevada. Photo caption "Controlled burning – Snake Lake, Plumas National Forest. Light burning. Fire burning uphill in early morning against wind. No. 41638-A. California Forest Experiment Station." E.N. Munns photographer. 5–27–19.

An analysis of SSPM Jeffrey pine-mixed conifer forests approximately 5 km northwest of the current study site (the 7 ×7 grid) found that they are also in an environment characterized by low levels of competition, which was similar to Sierra Nevada mixed-conifer forests in 1911 (Murphy et al., 2021). The average relative stand density index of these SSPM forests was below 35 % indicating that most of them are in the "Free Competition" and "Partial Competition" zones with regard to density dependent impacts on inter-tree competition (Murphy et al., 2021). Similar to contemporary SSPM forests, 80 % of 1911 Sierra Nevada mixed-conifer forests were in the "Free or Partial Competition" zones, but in 2011, 88 % of these were in "Full Occupancy" or "Imminent Mortality" zones (North et al., 2022) reflecting a very vulnerable competitive environment from 100-years of fire suppression. When these conditions were subjected to a hot, 4-year drought (2012–2015), over 120 million trees died in the southern and central Sierra Nevada and this increased fire hazards tremendously (Young et al., 2017; Stephens et al. (2022)).

An earlier drought (1999–2003) occurred in conifer forests in the San Bernardino and San Jacinto Mountains of southern California that killed millions of trees (Eatough-Jones et al., 2004) increasing snag densities to approximately 125 ha$^{-1}$ (Sims, 2004; Stephens and Fule, 2005) highlighting the vulnerably of these forests to severe mortality without fire. In contrast, similar bark beetle–induced tree mortality from the same drought did not occur in the SSPM where only 1.25 snags ha$^{-1}$ were created (Stephens and Fulé, 2005) highlighting the high resilience of SSPM forests.

## 5. Conclusion

Every year the staff of the SSPM National Park suppress many fires believing that they are potentially dangerous to visitors and to reduce smoke impacts for the astronomical observatory which is one of the largest in this area of North America. Another challenge regarding fire suppression is the staff at the SSPM National Park are a combination of federal and state employees; the park is co-managed by the State Government and the National Commission for Natural Protected Areas (CONANP). When the capacity of these entities is exceeded, the Federal Government steps in with the support of the National Forestry Commission (CONAFOR) to aid in fire suppression activities.

The parks decision to implement fire suppression is driven by the unpredictable behavior of wildfires, compounded by the limited number of personnel (only three rangers per shift), insufficient infrastructure, and lack of specialized equipment or financial resources. Park managers believe fire management efforts are crucial with early detection and suppression facilitated through observation towers. The presence of the largest astronomical telescope in this region of North America complicates fire management and the skies of the SSPM are known to be some of the clearest in the world (Cruz-Gonzales et al., 2004). However continued fire suppression will continue to increase fire hazards and place the telescope at risk as was the case when the large telescope complex in Canberra, Australia, was destroyed by a 2003 wildfire (Fig. 6).

The forests of the SSPM have seen an increase in fire hazards over the last 25-years but the good news is they are still in relatively good condition regarding fire hazards. Prescribed fire could easily be applied to SSPM forest to counter the relatively small increase in fuel loads and tree densities detected in this work without the need for mechanical manipulation (Table 1, Fig. 3); managed wildfire from lightning ignitions could also be an effective treatment and could use landscape features such as dry creek beds, rock outcrops, and roads, for fire containment. Forest and fire managers in the western US would like to have such conditions to burn in versus current US conditions that are much more hazardous (Hagmann et al., 2021). Restoration and stewardship of resilient forest structures is the only way forward to conserve the frequent-fire forests of the Sierra Nevada, southern California

**Fig. 6.** Telescope destroyed by wildfire at the Mount Stromlo Observatory near Canberra, Australia, on January 18th, 2003. Photo by Scott Stephens.

mountains, and elsewhere in the western US (Stephens et al., 2020; Hessburg et al., 2021) and the SSPM can provide important insights into this process.

## CRediT authorship contribution statement

**Hiram Rivera Huerta:** Writing – review & editing, Writing – original draft, Project administration. **Christina Fossum:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Brandon M. Collins:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Scott Stephens:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation, Conceptualization.

## 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 will be made available on request.

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