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ORIGINAL RESEARCH

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# Fuel load, stand structure, and understory species composition following prescribed fire in an old-growth coast redwood (*Sequoia sempervirens*) forest

David Cowman<sup>1</sup> and Will Russell<sup>2\*</sup> 

## Abstract

**Background:** With the prevalence of catastrophic wildfire increasing in response to widespread fire suppression and climate change, land managers have sought methods to increase the resiliency of landscapes to fire. The application of prescribed burning in ecosystems adapted to fire can reduce fuel load and fire potential while minimizing impacts to the ecosystem as a whole. Coast redwood forests have historically experienced fire from both natural and anthropogenic sources, and are likely to respond favorably to its reintroduction.

**Results:** Random sampling was conducted in three burned sites and in three unburned sites, in an old-growth coast redwood (*Sequoia sempervirens* [D. Don] Endl.) forest. Data were collected on fuel, forest structure, and understory species composition and compared between treatments. Downed woody fuel, duff depth, litter depth, and density of live woody fuels were found to be significantly lower on sites treated with fire compared to unburned sites. Density of the dominant overstory canopy species, coast redwood and Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco), remained consistent between treatments, and the abundance of herbaceous understory plant species was not significantly altered by burning. In addition, both downed woody fuel and live fuel measures were positively correlated with time since last burn, with the lowest measures on the most recently burned sites.

**Conclusions:** Our results indicated that the use of prescribed burning in old-growth redwood forests can provide beneficial reductions in live and dead surface fuels with minimal impacts to overstory trees and understory herbaceous species.

**Keywords:** coast redwood, controlled burning, duff depth, fuel reduction, litter depth, stand composition, stand structure

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## Resumen

**Antecedentes:** Ante la prevalencia de fuegos catastróficos incrementándose en respuesta a la prolongada supresión de incendios y al cambio climático, los gestores de recursos han buscado métodos para incrementar la resiliencia de los paisajes al fuego. La aplicación de quemas prescriptas en ecosistemas adaptados al fuego puede reducir la carga de combustibles y el potencial de incendios, mientras se minimizan los impactos del ecosistema como un todo. Los bosques costeros de secuías han experimentado fuegos históricos de origen tanto humano como naturales y es probable que respondan favorablemente a su reintroducción.

**Resultados:** Un muestreo al azar fue conducido en tres sitios quemados y en tres no quemados, en un bosque maduro de secuías costeras (*Sequoia sempervirens* [D. Don] Endl.). Los datos colectados fueron sobre combustibles, estructura del bosque, y composición de especies del sotobosque, y comparados entre tratamientos. El combustible leñoso caído, la profundidad de la capa de combustible leñoso orgánico, la profundidad de la broza, y la densidad de combustibles leñosos vivos fue menor sobre sitios tratados con fuego que en los no tratados. La densidad de las especies dominantes del dosel, la secuía costera y el abeto de Douglas (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco), permanecieron consistentes entre tratamientos y la abundancia de herbáceas del sotobosque no fue alterada por las quemas. Adicionalmente, tanto el combustible leñoso orgánico caído y la medición del combustible leñoso vivo estuvieron positivamente correlacionados con el tiempo desde la última quema, con los menores valores medidos en los sitios más recientemente quemados.

**Conclusiones:** Nuestros resultados indican que la aplicación de quemas prescriptas en bosques maduros de secuías costeras puede proveer de reducciones beneficiosas en combustibles vivos y muertos superficiales, con un mínimo impacto en árboles del dosel superior y en las especies herbáceas del sotobosque.

## Abbreviations

- BBRSP: Big Basin Redwoods State Park  
 DBH: Diameter at Breast Height  
 JREB: Johansen Road (East) prescribed burn project (Burned)  
 NERU: North Escape Road sample site (Unburned)  
 OVSB: Ocean View Summit prescribed burn project (Burned)  
 SUNU: SUNset trail sample site (Unburned)  
 S2SB: Skyline to (2) the Sea prescribed burn project (Burned)  
 S2SU: Skyline to (2) the Sea prescribed burn project (Unburned)

## Background

The nature of fire in the coast redwood (*Sequoia sempervirens* [D. Don] Endl.) forest is complex and unpredictable due to topographic variation, complex weather patterns, and an evolving regime of anthropogenic disturbance (Varner and Jules 2017). Occurring in coastal regions with frequent maritime fog during the dry season, and relatively low lightning storm activity during the dry season, naturally occurring fires in *S. sempervirens* forests have been historically low compared to many other forest types in California (Keeley 2005). With human settlement in the region, the majority of fires became anthropogenic in origin (McBride 1983). Indigenous burning generally resulted in low-intensity surface fires, with higher frequencies occurring in close proximity to grasslands,

oak (*Quercus* L.) woodlands, and indigenous settlements (Greenlee and Langenheim 1990; Stephens and Fry 2005; Lorimer et al. 2009; Jones and Russell 2015). Over time, the frequency and seasonality of fire has changed with cultural land use practices (Stuart 1987; Greenlee and Langenheim 1990). Initially, fire frequency remained relatively high following European settlement, but a shift in fire policy in the early twentieth century led to a dramatic decline in the occurrence of fire as a result of institutional fire suppression. Concern over the effects of a century of fire suppression on fuel load and forest composition has led managers to consider introducing controlled burning to coast redwood forests in an effort to mimic the low-intensity fire regime of the indigenous period (Stuart 1987; Keeley 2002).

*Sequoia sempervirens* maintains a host of adaptations to fire, including prolific vegetative sprouting, thick fibrous bark, and a high canopy (Barbour et al. 2001; Varner et al. 2017; Stephens et al. 2018), that allows canopy to be retained, or quickly reestablished, after fire (Lazzeri-Aerts and Russell 2014). As a result, plant species associated with *Sequoia sempervirens* are generally dependent on closed-canopy conditions, but also exhibit some adaptations to fire (Busing and Fujimori 2002). *Sequoia sempervirens* has a competitive advantage over associated tree species following fire, in part because of prolific post-fire reproduction (Lazzeri-Aerts and Russell 2014). In addition, larger-diameter trees (>30 cm diameter at breast height [DBH]) retain lower mortality rates than smaller-diameter trees following fire (Lazzeri-Aerts and

Russell 2014; Engber et al. 2017), due in part to thicker bark and increased canopy height with age (Barbour et al. 2001). However, changes to the fire regime can result in shifts in species dominance (relative cover of individual species divided by total cover of all species), which in turn can affect fuel beds and thus fire behavior, timing, and intensity (Mack and D'Antonio 1998; D'Antonio and Vitousek 1992; Brooks et al. 2004; Metz et al. 2013).

The three basic factors that influence fire behavior are fuel, weather, and topography (Biswell 1989). Weather and topography are largely unmanageable; thus, fuel reduction and vegetation management are used by land managers to mitigate high-intensity wildfires. Due to its massive size and long-lived nature, *S. sempervirens* produces the largest fuel load of any ecosystem type ever recorded, with some studies estimating total fuel load between 252 and 619 Mg ha<sup>-1</sup> (Busing and Fujimori 2002; Norman et al. 2009). However, total fuel load may not be the most useful factor in predicting fire severity. Factors that influence fire behavior include fuel bed depth, litter depth, duff depth, density of juvenile seedlings and sprouts, as well as receptive fuel bed moisture content (Keyes and Varner 2006). Fuel type and continuity, both vertical and horizontal, help dictate a fire's rate of spread and intensity. Continuous fine woody fuels (<7.6 cm diameter) allow fire to ignite and spread rapidly, whereas a high load of coarse woody fuels (>7.6 cm diameter) are slower to ignite but will continue to burn longer and generate more energy (Biswell 1989).

As a means of modifying potential fire behavior within the *S. sempervirens* ecosystem, land managers have employed several methods including variable density thinning, strategically situated shaded fuel breaks, and prescribed fire. A host of impacts are associated with the use of silvicultural treatments in the *S. sempervirens* forest type, however (Loya and Jules 2008; Russell and Michels 2010; Hanover and Russell 2018). And although fuel structure in *S. sempervirens* forest has been well described (Finney and Martin 1993), there is little available research on the impacts of prescribed fire on fuels and associated plant communities. Goals of prescribed burning can include the reduction of fuel load (including live and downed woody material), consumption of receptive fuel beds, reduction in juvenile and hardwood stems, and disruption of horizontal fuel continuity and vertical fuel arrangement (Biswell 1989).

The purpose of this study was to quantify the effects of prescribed burning in the *S. sempervirens* understory in regard to fuel load, forest stand composition, structure, and understory species assemblage. While the impacts of fire suppression continue to

compound, and frequency and intensity of wildfires increases, a renewed focus has been placed on the fire prevention and fuel manipulation phase of forest management, with impacts to understory plant species and overall forest health increasingly becoming a secondary concern.

## Methods

### Study sites

Big Basin Redwoods State Park (BBRSP) is the oldest state park in California, USA, located approximately 37 km northwest of the city of Santa Cruz, in the Santa Cruz Mountains. The Park rests in two county jurisdictions: Santa Cruz and San Mateo counties. The majority of BBRSP was set aside in 1902 via the passing of a 1901 State bill creating California Redwood Park. In 1927, California Redwood Park was renamed Big Basin Redwoods State Park. A total of ~3110 hectares were set aside in the initial creation of the Park to protect old-growth *S. sempervirens* stands from the rapid expansion of logging operations. In 1916, an additional ~1532 hectares were added to the Park, including the lands described in this project.

Big Basin Redwoods State Park is in the southern end of the Marine West Coast Climatic Zone (Martin 1998). To the south and east of the Park lies the Mediterranean Climatic Zone, which heavily influences the climate of the Park as well. Due to its proximity to the coast and maritime influence, BBRSP does not experience extreme seasonal changes and exhibits high relative humidity and consistent temperatures throughout much of the year (Martin 1998).

Elevation within BBRSP ranges from sea level in the western portion of the Park to just over 600 m; however, the portion of the Park composed of primarily old-growth *S. sempervirens* ranges from approximately 300 to 600 m in elevation. The majority of the roughly 10 800 ha of old-growth *S. sempervirens* resides on the eastern portion of the Park, near Park headquarters.

Three sample sites were selected in each of two treatments (burned and unburned). Data retrieved from the California Department of Parks and Recreation (California State Parks) regarding prescribed fire plot boundaries and areas of old-growth *S. sempervirens* were utilized to select plot locations on maps created on ArcGIS.

The burned sites represented three previous prescribed-fire burn sites, most recently experiencing fire in 1999, 2007, and 2011 (Table 1, Fig. 1). Sampling occurred on sites of similar biotic and abiotic conditions. The prescribed-fire sites included the Ocean View Summit Project (OVSB), Upper Skyline to the Sea Project (S2SB), and the Johansen Road East Project (JREB) (Table 1). The unburned sample sites included the Skyline to the Sea Project (S2SU), the North Escape Road site (NERU), and

**Table 1** Sample site descriptions and characteristics for areas treated with prescribed fire, as well as untreated controls, in Big Basin Redwoods State Park, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. Sites include: Ocean View Summit (OVSB), Skyline to the Sea burned (S2SB), Johansen Road East (JREB), Sunset Trail (SUNU), Skyline to the Sea unburned (S2SU), North Escape Road (NERU). Lowest RH = lowest humidity recorded on burn days; Highest RH = highest humidity recorded on burn days

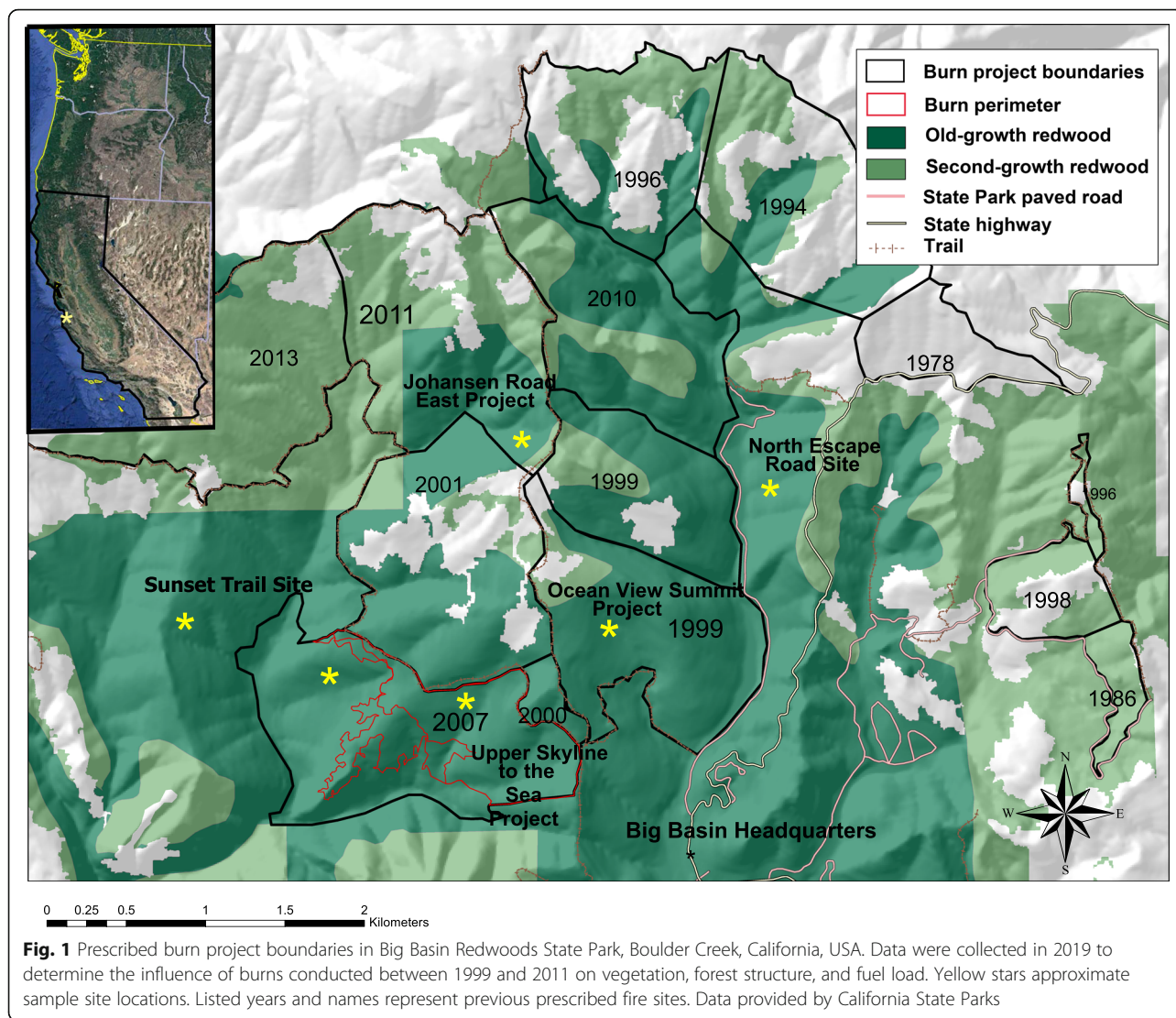
	Prescribed-burned sample sites			Unburned sample sites		
	OVSB	S2SB	JREB	SUNU	S2SU	NERU
Year burned	1999	2007	2011	NA	NA	NA
Area burned (ha)	~109	146.2	206.7	NA	NA	NA
Elevation range (m)	410 to 472	304 to 439	413 to 492	259 to 340	357 to 425	307 to 360
Mean aspect (°)	142	237	241	240	265	144
Slope range (%)	0 to 51	12 to 65	16 to 62	14 to 49	11 to 55	5 to 40
Ignition dates	2 Nov 1999 to 8 Jan 2000	9 to 24 Nov and Jan 2007	19 Oct 2011 to 4 Nov 2011	NA	NA	NA
Lowest RH (%)	35	37	12	NA	NA	NA
Highest RH (%)	100	100	100	NA	NA	NA
Fire activity	Slow backing fire with intermittent runs.	Backing fire with intermittent runs and torching.	Backing fire with intermittent runs and torching. 0.4 ha slop-over	NA	NA	NA

finally the Sunset Trail site (SUNU). For all sample sites, the last letter of the acronym refers to “burned” or “unburned” treatments” “B” for sites that had received prescribed burning or “U” for sites that were unburned by prescribed fire. It should be noted that all sites experienced the same wildfire in 1936, so that the time since the last burn for OVSB at the time of analysis was 20 yr, for S2SB was 12 yr, for JREB was 7 yr, and 83 yr for all unburned sites. Although all of the sampled locations had slight variations in topographic and microclimatic conditions, they had similar overstory dominance, plant community composition, seasonal moisture levels, and soil types (loam or sandy loam), allowing credible comparisons regarding fire effects on ecosystem composition (Table 1). Additionally, information on prescribed-fire operations was limited and represents a compilation of handwritten and typed notes from spot weather forecasts on burn days (OVSB and S2SB), conversations with fire managers on site, and Department of Parks and Recreation daily records of weather (JREB). Ideal conditions for burns were described in prescribed-burn plans for the three projects. Plans called for a relative humidity of 25 to 89%, air temperature of 45 to 75 degrees Fahrenheit, wind speed of 0 to 16 km h<sup>-1</sup>, and a 10-hour dead-fuel moisture of 8 to 14% for ignitions to commence. Additionally, primary ignitions were only permitted if at least 3.81 cm of precipitation had fallen during the rainy season, or 2.54 cm if no rain had fallen prior to 1 November. Additionally, ignition patterns for the three burns typically began with perimeter ignitions along ridgetops, followed by flanking and interior strip ignition. In poor burn environments, when

dead-fuel moisture was too high, ignitions were limited to large accumulations of fuel, or “jackpots.” Finally, limited ignitions by helicopter were attempted for the JREB plot.

### Sample design

Sampling was conducted using 20 randomly selected 10 m diameter circular plots in each of the three sites that experienced controlled burning, and 20 10 m diameter plots randomly selected in ecologically similar unburned sites (Lazzeri-Aerts and Russell 2014; Scherer et al. 2016; Hanover and Russell 2018). Ten-meter diameter plots were chosen because they were large enough to capture tree density and were small enough to be manageable for meticulous measurements of juvenile tree species density (Reid and Thompson 1996; Brower et al. 1998). A minimum sample size of 20 plots per site was employed, based on a power analysis conducted in similar *S. sempervirens*-dominated old-growth forest utilizing stand density and species richness as variables (Russell and Michels 2010). This resulted in a total of 120 sampled plots: 60 from areas that experienced prescribed fire, and 60 from areas that did not experience prescribed fire. All plots were located at least 10 m from adjacent plots, 10 m from special habitat types (*i.e.*, riparian or rocky outcroppings), and approximately 200 m from paved roads, to avoid edge effects on sampled areas (Jones and Russell 2001; Russell and Michels 2010). All trees with 50% or more basal area within plot delineation boundaries were inventoried and measured. Each plot was further broken down into four quadrants in order to make ocular estimates of ground cover more accurate.



**Field sampling**

Sampling occurred during the summer of 2019. Slope, aspect, elevation, and canopy cover were recorded at plot center, in addition to GPS coordinates using a Garmin Etrex 20 GPS unit (Garmin Ltd., Olathe, Kansas, USA). In order to determine percent canopy cover within each plot, a convex spherical densiometer was used from plot center, and readings were taken in each cardinal direction (Korhonen et al. 2006). Total woody and herbaceous cover and dominance was determined using ocular estimates in the four subdivided quadrants within the plot, resulting in a percent cover for each species. The percent-cover values from the four quadrants were then averaged for a plot-level cover estimate. Unknown species were collected and identified using the *The Jepson Manual* (Baldwin et al. 2012).

Each tree with at least 50% of its basal area within the plot boundary and greater than 10 cm DBH was

identified to species. Diameter at breast height (DBH) was taken 1.4 m from the ground surface along the uphill side of the tree. Trees with multiple stems were considered separate if the point of separation occurred below 1.4 m from the soil surface. Trees less than 10 cm DBH were counted, identified, and recorded separately into seedlings and sprouts, and sapling delineations (<1 m in height and >1 m in height, respectively). Trees were recorded as either live or dead; burned trees with any residual growth or sprouting were considered live (Lazzeri-Aerts and Russell 2014).

To assess dead and downed woody fuel load within the burn sites, the planar intersect technique provided in Brown (1974) was utilized. Two transect lines were sampled from the plot center of each 10 m diameter plot with the first extending 11.34 m along the dominant slope of the plot, and the second extending 90 degrees from the first transect line in the clockwise direction.

For fuel load assessments, the 10 m diameter plots only served to determine the beginning point for transect lines. All woody fuels intersecting the transect plane up to 1.52 m vertically were tallied or measured by size class, including fuel depth (defined as dead material measured from its highest point to the top of the litter layer, litter (defined as fresh needles, leaves, twigs, and cones measured to the top of the duff layer); and duff (defined as partially decomposed organic material measured from the bottom of the litter layer to the mineral soil). Fuels intersecting the transect line and extending vertically 1.83 m were broken down into predetermined size classes that represented 1-hour (0 to 0.64 cm), 10-hour (6.4 to 2.54 cm), 100-hour (2.54 to 7.62 cm), and  $\geq 1000$ -hour ( $\geq 7.6$  cm) fuels (Brown 1974).

#### Data analysis

Fine and coarse woody fuels were analyzed using calculations detailed in Brown (1974) to attain mean fuel load in tons per acre and then converted to metric tons per hectare ( $\text{Mg ha}^{-1}$ ) for each time-lag class (1-hour, 10-hour, 100-hour, and  $\geq 1000$ -hour). Calculations were made for each individual transect and then averaged across burn sites. In addition, fuel load estimates were made for the total of each sample site, combining transect lengths per sample site. Calculations for fine woody fuels (1-hour, 10-hour, and 100-hour,) were determined using Equation 1, provided by Brown (1974):

$$\text{Fine Woody Fuel Load } (\text{Mg ha}^{-1}) = \frac{knd^2s_{oc}ac}{Nl}, \quad (1)$$

where  $k$  is a constant of 11.64 (Brown 1974),  $n$  represents the number of individual particles counted in each size class per transect,  $d^2$  is the square of the quadratic mean diameter of each size class,  $s_{oc}$  is the composite specific gravity,  $a$  is the composite angle correction factor for each size class,  $c$  is the average transect slope correction factor, and  $Nl$  is the transect length. The slope correction factor ( $c$ ) for each individual transect line estimate was dependent upon the slope of that transect line (%), and was calculated using Equation 2:

$$c = \sqrt{1 + \left(\frac{\text{percent slope}}{100}\right)^2} \quad (2)$$

For composite transect line calculations yielding a single fuel load estimate per sample site, the mean slope correction factor was utilized. For all other constant values ( $d^2$ ,  $a$ , and  $s_{oc}$ ), values found in Brown (1974) were used for non-slash, conifer, and Western species.

Fuel load for  $\geq 1000$ -hour fuels ( $\geq 7.62$  cm) were calculated using Equation 3 from Brown (1974):

$$\text{Coarse Woody Fuel Load } (\text{Mg ha}^{-1}) = \frac{k(\sum d^2)s_{oc}ac}{Nl}, \quad (3)$$

where all variables mentioned above are the same and  $\sum d^2$  is the sum of the diameters of fuel particles (sound and rotten) squared (Brown 1974). Thousand-hour sound and rotten calculations were made separately and then combined into a single value. For all diameter estimates, measurements were made in inches and used to calculate fuel loading in tons per acre and later converted into metric tons per hectare ( $\text{Mg ha}^{-1}$ ).

Statistical analyses were performed using R software version 3.4.3 (R Development Core Team 2017), with an  $\alpha$  level of 0.05 used to determine statistical significance for all statistical analyses. Dependent variables, including duff depth, litter depth, fuel depth, canopy cover, fuel load, understory cover, and stand density, were tested for normality and homogeneity of variances using Shapiro Wilk's (Srivastava and Hui 1987) and Fligner Killeen's (Fligner and Killeen 1976) tests, respectively. Spearman rank order correlations were used to determine correlational relationships between dependent variables with time since burn (McCune and Grace 2002). Nested analysis of variance tests (ANOVA), with the nlme package in R, were used for variables averaged at the unit level to assess differences between burned and unburned treatments, with sample site considered as a random mixed effect (Laird and Bates 1988). To assess differences in stand structure of mature canopy trees, all stems greater than 10 cm DBH were separated into six predetermined size classes (10 to 24 cm, 25 to 49 cm, 50 to 99 cm, 100 to 149 cm, 150 to 199 cm, and 200+ cm).

#### Results

Spearman rank order tests indicated correlations between the time since the last fire and several fuel load metrics including duff depth, litter depth, coarse woody fuel load ( $>7.6$  cm diameter,  $\text{Mg ha}^{-1}$ ), and 1-hour fuel load ( $\text{Mg ha}^{-1}$ ) (Table 2, Fig. 2).

Coarse woody fuel load, duff depth, and litter depth were all found to be significantly lower in burned versus unburned treatments, with duff depth 49.8% lower, litter depth 11.85% lower, and coarse woody fuels 41.31% lower. However, no statistical differences were noted for fine woody fuels or fuel depth (Table 3).

#### Stand composition and structure

Spearman's coefficient tests indicated a positive correlation between time since fire and total stand density, density of sapling-sized stems ( $<10$  cm DBH,  $>1$  m height), and the density and relative basal dominance of *Notholithocarpus densiflorus* (Hook. & Arn.) Manos, Cannon & S. H. Oh (Table 2). The combined density of mature-sized trees ( $>10$  cm DBH) was lower on burned versus unburned plots

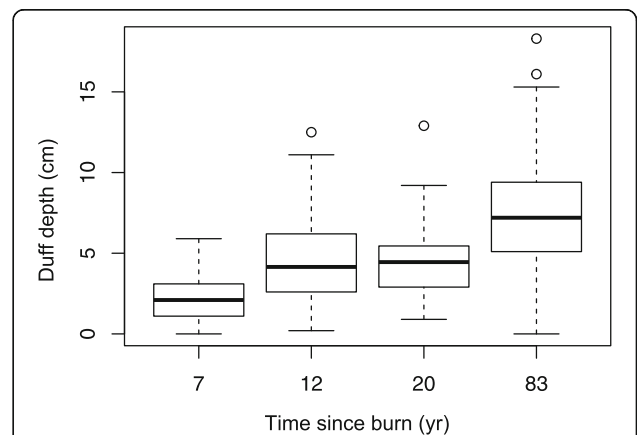
**Table 2** Spearman rank order correlation values (Rho) for dependent variables with time since fire. Analyses were performed on six sample sites, representing four times since burn. Times since burn include 7 yr, 12 yr, 20 yr, and 83 yr, in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load

Variable	P	Rho
Duff depth (cm)	<0.0010	0.60
Litter depth (cm)	<0.0010	0.19
Fuel depth (cm)	0.33	-0.045
Coarse woody fuel load (>7.6 cm diameter, Mg ha <sup>-1</sup> )	0.014	0.15
Fine woody fuel load (<7.6 cm diameter, Mg ha <sup>-1</sup> )	0.94	0.0052
1-hour fuel load (Mg ha <sup>-1</sup> )	<0.0010	0.40
10-hour fuel load (Mg ha <sup>-1</sup> )	0.20	0.084
100-hour fuel load (Mg ha <sup>-1</sup> )	0.30	-0.067
Canopy cover (%)	0.0020	0.28
<i>Sequoia sempervirens</i> stand density (stems ha <sup>-1</sup> )	0.94	-0.010
<i>Notholithocarpus densiflorus</i> stand density (stems ha <sup>-1</sup> )	0.0020	0.29
Total stand density (stems ha <sup>-1</sup> )	0.013	0.23
<i>Sequoia sempervirens</i> relative basal dominance (%)	0.12	-0.14
<i>Notholithocarpus densiflorus</i> relative basal dominance (%)	0.0090	0.24
Total basal area (m <sup>2</sup> ha <sup>-1</sup> )	0.85	-0.020
Density of stems <10 cm DBH and <1 m in height (stems ha <sup>-1</sup> )	0.15	0.13
Density of stems <10 cm DBH and >1 m in height (stems ha <sup>-1</sup> )	<0.0010	0.52
Understory species richness per plot (number of species)	0.35	-0.090
Understory cover per plot (%)	0.36	-0.080
Shrub species richness per plot (number of species)	0.0060	0.25
Shrub cover per plot (%)	<0.0010	0.34

(Table 4), with the majority of this variation occurring in regard to *N. densiflorus*. Similarly, combined juvenile stem density (<10 cm DBH) was lower on burned sites, with the majority of variation found for *N. densiflorus*, with no significant differences found for the other species present.

Nested ANOVA tests comparing individual size class density between treatments indicated no significant differences for any size class with regard to *S. sempervirens* or *Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco. However, tests comparing *N. densiflorus* stand density by size class between the two treatments indicated significant differences in both the juvenile size classes (seedling and sprout, and sapling), as well as the 10 to 24 cm and 25 to 49 cm size classes (Fig. 3). The largest difference was in density of *N. densiflorus* saplings, resulting in a visible difference in subcanopy ladder fuels between treatments (Fig. 4).

Mean percent canopy cover varied between burned and unburned treatments ( $F = 16.75, P < 0.001, df = 1$ ); with a mean percent canopy cover of  $91.43 \pm 0.51$  (SE) on burned sites compared to  $93.92 \pm 0.34\%$  on unburned sites



**Fig. 2** Boxplots and stripchart of duff depth (cm) differences with time since burn (yr) for six sample sites in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. Times since burn 7 yr, 12 yr, and 20 yr represent sites that were burned in 1999, 2007, and 2011–2012, respectively. Time since burn 83 yr represents three reference sample sites that were most recently burned in a wildfire in 1936. Boxes represent the upper and lower quartiles, whiskers represent full range of data excluding outliers, circles represent outliers



**Table 3** Comparison of receptive fuel bed and fine woody fuel (FWF; <7.6 cm diameter) and coarse woody fuel (CWF; >7.6 cm diameter) loading between burned and unburned plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load

Fuel variable	Mean loading (SE)		ANOVA results		
	Unburned	Burned	F	P	df
Duff depth (cm)	7.47 (0.22)	3.75 (0.15)	198.11	<0.0010	1
Litter depth (cm)	5.23 (0.18)	4.61 (0.15)	4.67	0.031	1
Fuel depth (cm)	10.1 (1.18)	10.83 (1.20)	1.073	0.30	1
FWF (Mg ha <sup>-1</sup> )	6.11 (0.4)	6.39 (0.42)	0.095	0.76	1
CWF (Mg ha <sup>-1</sup> )	122.56 (26.67)	71.92 (19.44)	5.035	0.026	1

No significant differences were noted in total basal area (m<sup>2</sup> ha<sup>-1</sup>) of all tree species combined between burned and unburned sites (Table 5). Additionally, basal dominance of *N. densiflorus*, *S. sempervirens*, *Quercus* spp., *Arbutus menziesii* Pursh, and *P. menziesii* var. *menziesii* showed no statistically significant differences between burned and unburned locations based on nested ANOVA results.

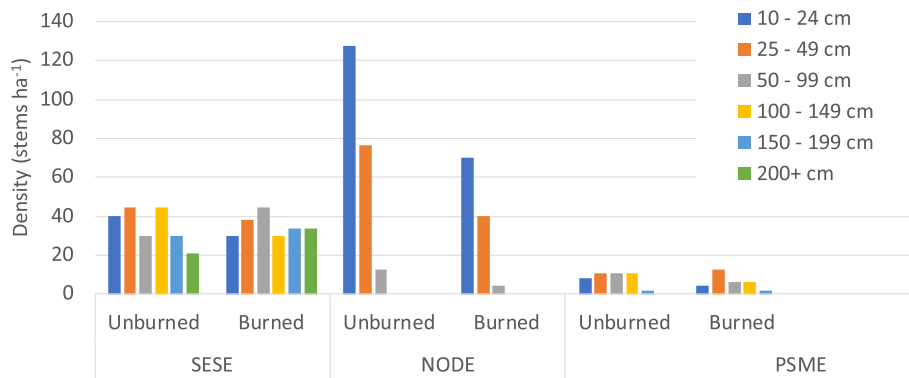
**Understory plant composition**

While no trends were noted between time since fire and total understory cover and richness, Spearman’s correlation analysis did indicate positive rank order correlations between woody shrub species richness and percent cover (Table 2). In addition, nested ANOVA tests indicated significant differences in shrub percent cover per plot and shrub species richness per plot between burned and unburned plots ( $F = 22.85, P < 0.001, df = 1$ , and  $F = 9.81, P = 0.0022, df = 1$ , respectively). Burned plots exhibited both lower percent shrub cover per plot as well as lower shrub species richness per plot, compared to unburned plots (Table 6). No statistically significant differences were indicated for herbaceous understory species richness cover between burned and unburned sites based on nested ANOVA results, and no indication of an increase in non-native species was noted.

The presence of individual understory species appeared to be generally independent of treatment with 25 of the 38 species recorded found in both the burned and unburned treatments (Table 7). Most of the shrub species recorded were low in abundance, with *Frangula californica* (Eschsch.) A. Gray and *Morella californica* (Cham. & Schltld.) Wilbur found only on unburned sites, and

**Table 4** Comparison of forest stand density (stems ha<sup>-1</sup>) of trees between burned ( $n = 60$ ) and unburned ( $n = 60$ ) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. SESE = *Sequoia sempervirens*, NODE = *Notholithocarpus densiflorus*, PSME = *Pseudotsuga menziesii*, ARME = *Arbutus menziesii*, QU spp. = all *Quercus* species combined. Dashes (-) indicate insufficient sample size for analysis

Tree	Mean density in stems ha <sup>-1</sup> (SE) able 5		Nested ANOVA results		
	Unburned	Burned	F	P	df
SESE >10 cm	207.96 (22.03)	205.84 (19.63)	0.0011	0.97	1
NODE >10 cm	216.45 (21.89)	114.59 (18.08)	15.36	<0.0010	1
PSME >10 cm	42.44 (10.75)	31.83 (10.77)	0.99	0.32	1
QU spp. >10 cm	6.36 (4.71)	0.00 (0.00)	1.97	0.16	1
ARME >10 cm	0.00 (0.00)	4.24 (4.24)	1.00	0.32	1
All trees >10 cm	473.22 (27.92)	356.51 (24.55)	10.10	0.0019	1
SESE <1 m	3 463.21 (1075.94)	2779.91 (479.04)	0.35	0.14	1
SESE >1 m	1 239.29 (677.52)	1088.62 (487.68)	0.036	0.85	1
NODE <1 m	6 992.21 (989.13)	4034.05 (661.12)	12.43	<0.0010	1
NODE >1 m	3 338.01 (337.62)	823.36 (127.34)	61.37	<0.0010	1
PSME <1 m	10.61 (6.27)	36.08 (13.57)	-	-	-
PSME >1 m	10.61 (6.96)	27.59 (15.46)	-	-	-
QU spp. <1 m	40.32 (17.77)	10.61 (6.27)	-	-	-
QU spp. >1 m	4.24 (2.98)	0.00 (0.00)	-	-	-
ARME <1 m	0.00 (0.00)	8.49 (8.49)	-	-	-
ARME >1 m	0.00 (0.00)	0.00 (0.00)	-	-	-
All trees <1 m	10 506.35 (1504.89)	6869.13 (745.38)	5.98	0.016	1
All trees >1 m	4 592.15 (683.72)	1939.57 (505.91)	30.88	<0.0010	1



**Fig. 3** Mature size class distribution of three dominant tree species, comparing burned and unburned treatments, in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. Within nested ANOVA tests, significant differences were noted exclusively within NODE in the 10 to 24 cm and 25 to 49 cm size classes. Species abbreviations are defined as follows: SESE = *Sequoia sempervirens*, NODE = *Notholithocarpus densiflorus*, PSME = *Pseudotsuga menziesii*

*Symphoricarpos albus* (L.) S. F. Blake found only on burned sites. *Vaccinium ovatum* Pursh, which was the most common shrub recorded across treatments, was more abundant in unburned versus burned plots. A similar pattern of distribution was noted for herbaceous understory

species, with only *Iris fernaldii* R. C. Foster, *Lysimachia latifolia* (Hook.) Cholewa, and *Polygala californica* Nutt. recorded across all sample sites. The only non-native species identified was *Epipactis helleborine* (L.) Crantz, which was found in both burned and unburned treatments.



**Fig. 4** Unburned and burned forest stand characteristics in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. The unburned image (A) is from the North Escape Road site (NERU), and the burned image (B) was from the 2011 Johansen Road East project (JREB). Images depict similar density and diameter distributions of *Sequoia sempervirens* and higher density of *Notholithocarpus densiflorus* in unburned sites. Photo credit: David Cowman, 2018

**Table 5** Comparison of relative mean basal dominance and basal area between burned ( $n = 60$ ) and unburned ( $n = 60$ ) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. SESE = *Sequoia sempervirens*, NODE = *Notholithocarpus densiflorus*, PSME = *Pseudotsuga menziesii*, ARME = *Arbutus menziesii*, QU spp. = all *Quercus* species combined

Tree	Relative mean basal area (SE)		Nested ANOVA results		
	Unburned	Burned	F	P	df
SESE	0.70 (0.05)	0.76 (0.05)	0.28	0.60	1
NODE	0.17 (0.04)	0.12 (0.04)	3.58	0.061	1
PSME	0.12 (0.04)	0.07 (0.03)	1.72	0.192	1
QU spp.	0.00 (0.00)	0.00 (0.00)	1.81	0.18	1
ARME	0.00 (0.00)	0.00 (0.00)	1.00	0.32	1
All trees basal area ( $\text{m}^2 \text{ha}^{-1}$ )	282.58 (29.66)	314.79 (37.87)	0.012	0.91	1

## Discussion

The management of fuels is of concern in old-growth *S. sempervirens* forests, as some of the highest fuel loads in any forest type have been recorded in coast redwood (Graham 2009). The results of this study indicated that prescribed fire was effective in reducing several measures of fuel load with no adverse impacts to associated understory species or increase in the abundance of non-natives species. Fuel load and fuel bed depth are known to influence the severity and rate of spread of fire (Nives 1979), and the reduction in fuel load, including coarse woody fuels, can limit the mortality for individual trees (Metz et al. 2011; Metz et al. 2013). The reduction of litter and duff depth were particularly important as *S. Sempervirens* produces the third most flammable litter of any coniferous species (Varner and Jules 2017), and excess duff can result in persistent smoldering around the base of live trees for some species, increasing mortality. In comparison, mechanical thinning treatments alone can increase, rather than decrease, the same measures, suggesting that prescribed fire is the preferred fuel mitigation option (Glebocki 2015). A lack of decline in fine woody fuel (<7.6 cm diameter) load after fire was not surprising as fine woody fuels are known to re-establish quickly after burning. Engber et al. (2017), for example, noted a full recovery of fine surface fuels

7 yr after burning. As a result, subsequent burns may be required to limit the impact of post-fire sprouting.

A post-burn decline in the abundance of woody shrubs and *N. densiflorus* in the smaller size classes (<10 cm DBH, >1 m height) was noted. Prescribed fire also appeared to reduce the dominance and density of *N. densiflorus*, a result consistent with Ramage et al. (2010) and Lazzeri-Aerts and Russell (2014). However, variation in the density of *N. densiflorus* has also been noted as a result of gap phase dynamics, so that the extent that prescribed fire was a driver of this variation is not clear (Hunter and Parker 1993; Hunter et al. 1999). Burning had little effect on *S. sempervirens* stand density within any of the size classes, which is largely consistent with Engber et al. (2017), who found no shift in overstory tree composition following prescribed fire. These findings are also consistent with Lazzeri-Aerts and Russell (2014), who found 100% survivorship of *S. sempervirens* greater than 7.5 cm DBH following fire.

In the woody shrub layer, the most drastic shift of species composition was in regard to cover of *Vaccinium ovatum*. Within coastal California, the majority of the *V. ovatum* native range has experienced infrequent fire intervals during pre-settlement times (Stuart 1987). Tirmenstein (1990) argued that this may have led to poorly developed adaptations to fire within the species. According to Martin (1979), *V. ovatum*

**Table 6** Comparison of herbaceous and shrub species richness and diversity between burned ( $n = 60$ ) and unburned ( $n = 60$ ) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load

Variable	Mean (SE)		Nested ANOVA results		
	Unburned	Burned	F	P	df
Understory richness (species per plot)	1.8 (0.2)	2.1 (0.2)	0.37	0.55	1
Understory percent cover (per plot)	2.9 (0.7)	7.3 (1.9)	4.00	0.050	1
Shrub richness (species per plot)	1.2 (0.1)	0.7 (0.1)	22.85	<0.0010	1
Shrub percent cover (per plot)	9.6 (2.0)	1.6 (0.5)	9.81	0.0022	1

**Table 7** Mean cover (%) of understory plant species found within six sample sites in Big Basin Redwoods State Park, Boulder Creek, California, USA. Data were collected in 2019 to determine the influence of burns conducted between 1999 and 2011 on vegetation, forest structure, and fuel load. Asterisk (\*) denotes non-native species. Dashes (-) mean species not found

Species	Mean cover (%)					
	Unburned			Burned		
	NERU	S2SU	SUNU	JREB	S2SB	OVSB
<b>Woody shrub species</b>						
<i>Frangula californica</i>	-	0.03	0.03	-	-	-
<i>Lonicera hispidula</i> (Lindl.) Douglas ex Torr. & A. Gray	0.6	1.7	0.5	0.06	0.5	0.4
<i>Morella californica</i>	-	0.6	-	-	-	-
<i>Rosa gymnocarpa</i> Nutt.	-	-	0.1	-	0.1	-
<i>Rubus ursinus</i> Cham. & Schltld.	0.4	-	-	0.05	-	-
<i>Symphoricarpos albus</i>	-	-	-	-	0.03	-
<i>Symphoricarpos mollis</i> Nutt.	-	0.03	-	-	-	-
<i>Toxicodendron diversilobum</i> (Torr. & A. Gray) Greene	0.09	0.01	-	0.05	-	-
<i>Vaccinium ovatum</i>	4.5	19.8	0.1	0.7	-	1.4
<i>Whipplea modesta</i> Torr.	-	0.4	-	0.9	0.5	0.09
<b>Herbaceous species</b>						
<i>Asarum caudatum</i> Lindl.	-	-	-	-	0.02	-
<i>Bromus</i> Scop. sp.	0.006	0.01	-	-	0.4	0.006
<i>Calamagrostis rubescens</i> Buckley	-	-	0.2	-	-	0.7
<i>Carex globosa</i> Boott	0.006	0.3	-	0.4	1.6	-
<i>Carex</i> L. sp.	-	-	-	-	1.2	0.9
<i>Carex tumulicola</i> Mack.	-	-	-	-	0.2	-
<i>Dryopteris arguta</i> (Kaulf.) Maxon	0.05	0.04	0.4	-	-	-
<i>Epipactis helleborine</i> *	0.03	-	0.04	0.2	0.01	-
<i>Equisetum arvense</i> L.	-	-	-	0.01	-	-
<i>Festuca occidentalis</i> Hook.	-	-	-	-	0.03	-
<i>Galium californicum</i> Hook. & Arn.	1.08	0.02	-	0.03	0.02	-
<i>Iris douglasiana</i> Herb.	-	-	0.4	-	-	-
<i>Iris fernaldii</i>	0.2	0.09	0.1	0.2	0.1	0.3
<i>Lysimachia latifolia</i>	0.04	0.2	0.05	0.1	0.9	0.4
<i>Maianthemum racemosum</i> (L.) Link	0.03	-	-	-	0.06	0.003
<i>Maianthemum stellatum</i> (L.) Link	0.03	-	-	-	-	-
<i>Oxalis oregana</i> Nutt.	0.5	0.4	3.06	0.2	12.5	-
<i>Pityrogramma triangularis</i> (Kaulf.) Yatsk., Windham & E. Wollenw.	-	-	-	0.003	-	-
<i>Polygala californica</i> Nutt.	0.2	0.09	0.1	0.02	0.1	0.1
<i>Polypodium californicum</i> Kaulf.	0.06	-	0.006	-	-	-
<i>Polystichum munitum</i> (Kaulf.) C. Presl	0.1	0.04	0.5	0.02	0.04	-
<i>Prosartes hookeri</i> Torr.	-	0.01	0.06	-	0.1	0.08
<i>Pteridium aquilinum</i> (L.) Kuhn var. <i>pubescens</i> Underw.	-	0.03	-	-	0.006	-
<i>Stachys bullata</i> Benth.	-	0.04	-	0.05	0.03	-
<i>Trillium ovatum</i> Pursh	0.1	0.01	0.03	-	0.04	0.01
<i>Vicia americana</i> ssp. <i>americana</i> Willd.	0.05	0.04	-	0.01	-	-
<i>Viola ocellata</i> Torr. & A. Gray	0.01	-	0.01	-	0.08	0.2
<i>Viola sempervirens</i> Greene	-	-	0.05	0.01	0.08	-

rarely reproduces via seed dispersal and has a seed bank and sub-surface root structure prone to mortality in the presence of duff-consuming surface fires with a long residence time. These factors, coupled with the timing of prescribed fires in this study, during the late fall and early winter months when live fuel moisture is low, could explain the lower presence and cover of *V. ovatum* in burned treatment plots.

Although a marginal difference was found in canopy cover between burned and unburned plots, there was no difference in tree species composition or structure of *S. sempervirens*. The difference in mean canopy cover between burned and unburned plots represented less than a 3% shift and was due to a reduction in the subcanopy layer of hardwood and juvenile tree species, rather than the creation of forest canopy gaps. And while changes in crown fuels were not measured directly, reduction in ladder fuels suggests a disruption of vertical-fuel continuity in these stands and a potential decline in crown-fire potential (Scott 2001; Cruz et al. 2004).

The absence of shifts in understory herbaceous plant composition following burning was encouraging. Mechanical fuel reduction can have adverse impacts on the *S. sempervirens*-associated herbaceous species and can provide opportunities for the invasion of non-native species (Loya and Jules 2008; Blair et al. 2010; Russell and Michels 2010; Hanover and Russell 2018). Intentional burning, at least in this case, did not appear to have negative impacts on herbaceous understory species.

## Conclusions

Prescribed fire in the southern extent of the *S. sempervirens* range has the potential to reduce fuel load while maintaining understory diversity and native species' assemblages. Positive correlations noted between similar variables and time since burn indicated that, in the absence of fire, *S. sempervirens* forest trends toward higher fuel load and less fire-tolerant characteristics. With a host of adaptations to disturbance and a relative lack of vulnerability to non-native species establishment, the *S. sempervirens* ecosystem is an ideal candidate for satisfying fuel reduction goals while maintaining ecological integrity. Evidence points to higher fire return intervals in *S. sempervirens* ecosystems with proximity to adjacent grasslands, shrublands, and oak woodlands (Greenlee and Langenheim 1990). Progressing forward into an uncertain climatic future, a crucial aspect of forest management will be satisfying fuel management goals while minimizing adverse ecological impacts, and creating more fire-tolerant ecosystems.

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## Authors' contributions

DC and WR contributed to the design of the study as well as preparation of the manuscript. DC collected all field data and performed data analysis. DC and WR read and approved the final manuscript.

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## Availability of data and materials

The datasets used or analyzed during the current study are available from WR on reasonable request.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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