LONG-TERM EFFECTIVENESS OF FUEL TREATMENTS IN OAK AND CHAPARRAL STANDS OF NORTHERN CALIFORNIA

By

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ABSTRACT

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Fuel reduction treatments are broadly implemented to reduce the risk of extreme wildfire. Yet, research on the long-term effectiveness and ecological consequences among these treatments is lacking. In this study, I examined short- and long-term changes in fuels and understory vegetation after treatment in chaparral and oak-dominated stands of Whiskeytown National Recreation Area. Treatments included mastication and spring burning, spring burning only, mastication only, and hand-thinning. Treatments were applied randomly to 1 to 2 units within each of 10 blocks. Two plots were established in each treatment unit and fuel and vegetation data was collected and analyzed at the block level (n=10). Results showed all treatments, except spring burn only, reduced live shrub height compared to the control. The combined mastication and spring burn treatment had up to 2.3 times higher live shrub density than the other treatments. Mechanical or manual only treatments promoted reductions in fine dead woody surface fuel loading compared to the control 15 years after treatment. There were subtle changes in the understory plant community, including an increase in species richness in the mastication and spring burn treatment and a decrease in species richness over time. The effects of fuel treatments on fuels and understory vegetation were highly varied with some level of trade-off in

effectiveness. Optimal fuel treatments will likely depend on the specific site objectives. However, results from this study indicate that mastication and hand removal treatments can provide substantial decreases in live and dead fuel loading over the long- term without substantial changes to the understory plant community.

ACKNOWLEDGEMENTS

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INTRODUCTION

Chaparral is a fire-prone evergreen shrubland ecosystem ranging from southwest Oregon to Baja California, Mexico and from the Coast Ranges to the Sierra Nevada (McMurray 1990; Fryer 2015). The prolonged summer drought conditions associated with the Mediterranean climate in this area and the characteristics of dominant chaparral species provides optimal conditions to sustain high severity crown fire (Barro and Conrad 1991; Keeley and Fotheringham 2001). Chaparral shrubs often produce highly flammable leaves and fine branches to facilitate fire (Keeley 1987; Barro and Conrad 1991; Keeley 1991) and many plants rely on, or are enhanced by, fire for propagation, making fire an integral process to chaparral plant communities (Keeley and Fotheringham 2001).

The high flammability of this ecosystem and its proximity to urban areas have prompted the application of fuel treatments throughout many regions. Due to the substantial amount of urban area adjacent to chaparral (Syphard *et al.* 2014), conflicting management objectives exist between limiting severe wildfire and maintaining the ecological integrity of the plant community (Keeley 2002, Keeley and Brennan 2012). Treatments that are beneficial in reducing risk of severe fire, may have the unintended impact if reducing the persistence of chaparral (Merriam *et al.* 2006). In spite of the widespread application of treatments over the past two decades, the efficacy of fuel treatments in chaparral ecosystems is not well understood and its effectiveness under extreme fire weather conditions has been questioned (Keeley and Fotheringham 2001; Keeley 2002; Keeley and Brennan 2012). Furthermore, the efficacy of these treatments will be increasingly tested with climate change and population growth increasing the likelihood of ignition and spread (Westerling and Bryant 2008).

Fuel treatments aim to reduce the risk of severe fire by reducing fuel loading and continuity (Agee and Skinner 2005). Manual and mechanical fuel treatment methods are often chosen over prescribed fire due to a number of complications including liability and air quality (Ottmar *et al.* 2001). For example, hand-thinning is a manual treatment that reduces density in a stand by harvesting and removing shrubs (Graham *et al*. 1999), and mastication is a mechanical treatment that uses machinery to reduce density by chipping mid-story vegetation into small woody surface fuels retained on site (Kane *et al.* 2009; Fornwalt *et al.* 2017). Manual and mechanical methods can be more effective than prescribed fire at reducing horizontal and/or vertical continuity of fuels (Kane *et al.* 2010; Schwilk *et al.* 2009; Wilken *et al.* 2017), while prescribed fire can be more effective at reducing surface fuel loading (Schwilk *et al.* 2009; Brennan and Keeley 2015). However, prescribed fire alone sometimes does not meet management objectives because of lower intensities that result from higher moisture conditions when burning outside the historical fire season (Ryan *et al*. 2013). Mechanical treatments followed by prescribed fire may be advantageous in some vegetation types due to the combined decreases in continuity and surface fuel loading (Stephens and Moghaddas 2005; Schwilk *et al.* 2009). If the management objective is to maintain a prolonged reduction in shrub fuels, the use of prescribed fire alone or in combination with mechanical treatments in stands dominated by obligate seeding shrubs can lead to increased shrub density due to fire-stimulated shrub propagation (Stephens *et al.* 2009; Kane *et al.* 2010), and thus potentially reducing the longevity of treatment effectiveness.

While fuel treatments are widely applied in many regions containing chaparral, only a few studies have reported on the long-term changes to fuel structures and reduced risk of severe fire behavior. Live shrub fuel cover in chaparral stands that were prescribed burned increased more than in masticated sites, with both treatments approaching pretreatment levels between eight and ten years (Brennan and Keeley 2015; Wilken *et al.* 2017). This relatively rapid increase in recovery of live shrubs following fuel treatments in chaparral suggests that the longevity of many treatments is relatively short lived, especially with resprouting shrubs. Dead woody surface fuels expectedly decreased in cover over time across a wide range of treatments including mastication in chaparral (Perchemlides *et al.* 2008; Brennan and Keeley 2015) but fine woody fuel loading generated from mastication can persist beyond 15 years (Reed 2016). Fire behavior in masticated fuel beds have been reported to have higher intensity and severity (Bradley *et al.* 2006; Knapp *et al.* 2011), but more research that examines the long-term responses of both live and dead woody surface fuels and the change in risk over time following an array of treatment options is warranted.

Monitoring the long-term ecological consequences of fuel treatments on chaparral plant communities is also needed. Maintaining or enhancing native species richness is necessary to preserve plant species important to wildlife (Longhurst 1978), cultural values and other resources (Anderson and Rosenthal 2015). Dominant shrub species, geophytes, and other plants rely on or are enhanced by the presence of fire for propagation (Keeley 1987, Keely 1991, Keeley 2007). Mechanical treatments used as a "fire-surrogate" may have undesired ecological consequences (Perchemlides *et al.* 2008). For instance, elevated fire frequencies above historical levels have been demonstrated to convert chaparral shrublands to exotic grasslands that in turn facilitates more frequent fire (Zedler *et al.* 1983; Brooks *et al.* 2004; Keeley and Brennan 2012). Increases in exotic grass cover following some fuel treatment types may increase the likelihood of type conversion of chaparral if followed by another disturbance within a sufficiently short time span (Merriam *et al.* 2006; Keeley and Brennan 2012).

Research on fuel treatment effectiveness in the northern California chaparral region is limited and existing information is often conflicting. For example, species richness increased following mechanical mastication treatment in one study (Potts and Stephens 2009), but did not increase in another similar study following hand removal or mastication (Perchemlides *et al.* 2008), or increased only in a combined mechanical mastication and prescribed fire treatments (Kane *et al.* 2010). Even when there were clear positive impacts of fuel treatments on understory vegetation, they often also had other negative impacts such as an increase in exotic species richness and cover (Kane *et al.* 2010; Fornwalt *et al.* 2017). In fact, some of these negative impacts can persist over long timespans. An elevated exotic species response was still present seven and ten years after mastication treatment in northern California chaparral (Perchemlides *et al.* 2008; Wilken *et al.* 2017). Inconsistencies in previous research indicates that site-specific information may be needed to anticipate understory vegetation responses to fuel treatments over time. There is a fair amount of research on chaparral in southern California (Keeley 2007) and much fewer studies in the northern California region. Better local information on the northern California chaparral community response to fire and fire-surrogate treatments could improve management decisions in these areas.

My study was originally established in 2002 in chaparral and oak stands of Whiskeytown National Recreation Area (Bradley *et al.* 2006) to examine the effectiveness and impacts of a suite of commonly used treatments on understory vegetation. The initial study examined vegetation and some fuel responses two years after treatment and determined prescribed burning in masticated sites led to undesirably intense and severe fire, whereas the site that only received prescribed fire experienced very low fire intensity, poor fuel consumption and other undesirable fire effects (Bradley *et al*. 2006). Utilizing this existing study, I further examined changes in fuels and understory vegetation 15 years after fuel treatments, including mastication and spring burn (Mast + Burn), spring burn only (Burn Only), mastication only (Mast), and hand-thinning (Hand-thin), applied to chaparral and oak-dominated stands. The specific research questions for this study were: 1) How does fuel loading and structure differ among treatments and vegetation types 15 years after treatment? And 2) does fuel treatment type and time since treatment influence understory vegetation at the community level? The results of this study will aid managers in deciding which treatments may best meet management objectives by providing much needed information on the short- and long-term fuel and vegetation responses in chaparral vegetation of northern California.

MATERIALS AND METHODS

Site Location

The study site was located in Whiskeytown National Recreation Area (40.6221° N, 122.5541° W) in the southeastern edge of the Klamath Mountains in Shasta County, northern California (Figure 1). The project area is 18.2 ha with elevation ranging from 381 to 457 m. Summers are hot and dry with temperatures often over 38°C between May to October. Winters are cold with occasionally heavy rainfall and sub-freezing temperatures between November and March. The average annual rainfall from 1981 to 2010 was 1,524 mm, 75 to 90% of which fell between November and April (PRISM Climate Group 2017). Soils are mostly Boomer gravelly loam on 15 to 30% slopes and Neuns very stony loam on 8 to 50% slopes (NRCS 2018).

The study site was classified into either a chaparral-dominated vegetation type or an oak-dominated vegetation type. The chaparral-dominated type did not contain overstory trees except knobcone pine (*Pinus attenuata*), while the oak-dominated type had an overstory tree and a mid-story shrub component. The dominant shrub species at the study site included whiteleaf manzanita (*Arctostaphylos viscida*), toyon (*Heteromeles arbutifolia*), and poison oak (*Toxicodendron diversilobum*) (Bradley *et al.* 2006). The dominant tree species included black oak (*Quercus kellogii*) and knobcone pine with minor overstory species including canyon live oak (*Quercus chrysolepsis*), grey pine (*Pinus sabiniana*), and interior live oak (*Quercus wislizeni*). The historical fire regime for chaparral in this area was characterized by low frequency, high intensity crown fires at an interval ranging from 30 to 150 years (Keeley 2007).

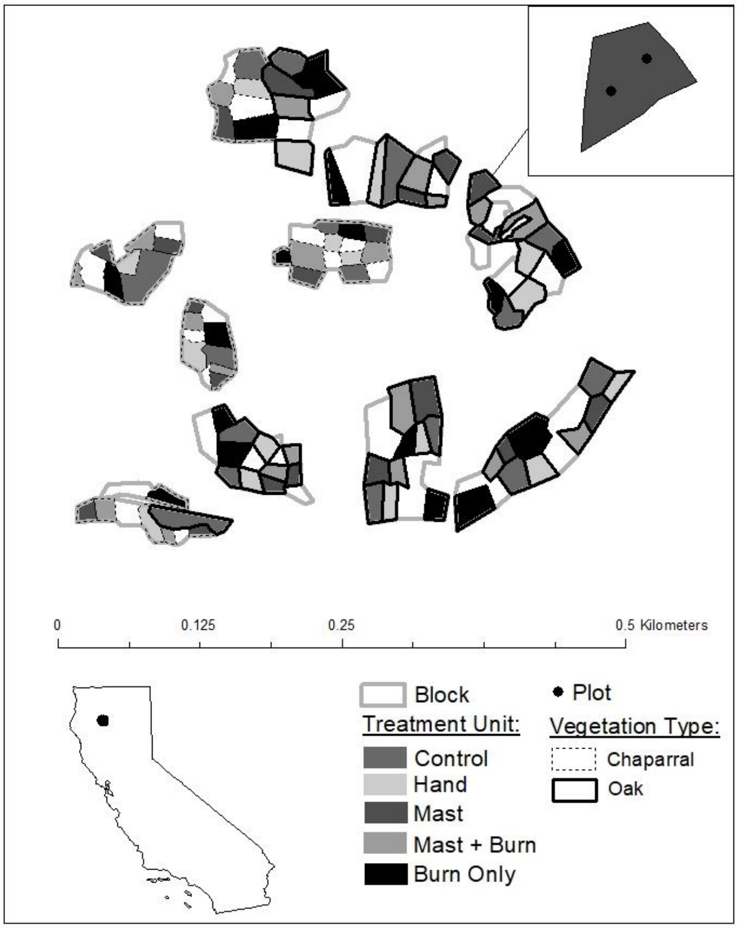


Figure 1. Study area and sample blocks at Whiskeytown National Recreation Area in northern California.

Experimental Design and Data Collection

The study site was established in 2002 with ten blocks ranging from 0.4 to 0.8 ha in size. Each block was broken up into treatment units and included one to two units (0.03 to 0.30 ha) of each of the five treatment types and contained two plots within each unit (Table 1). Treatment types, including Mast, Mast + Burn, Burn Only, Hand-thin, and control, were randomly assigned to each unit. The Hand-thin treatment occurred in February and March 2003 and brush was cut with chainsaws by crews, carried off site, piled and burned (Bradley *et al.* 2006). Mast treatments occurred in November 2002 using an ASV Posi-Track with an industrial brush-cutter to chip shrubs and small trees less than 4 m in height and to reduce understory shrub density by 60 to 95%. Prescribed fire occurred in the spring after oaks leafed out in April and May 2003. Drip torches were used to strip or spot ignite backing fires through each prescribed burn unit. At the time of burning, air temperature ranged from 15 to 22°C and relative humidity ranged from 34% to 73% with wind speeds averaging 3.2 km/hr with a maximum of 9.7 km/hr. Soil moisture conditions were relatively wet (0.3 to 0.4 kPa). These conditions fostered a low intensity surface fire with temperatures not exceeding 104°C. This fire behavior led to effects that often killed but did not consume shrubs. Conversely, the Mast + Burn treatment experienced much higher temperatures (average of 347°C) and high flame lengths (average of 74 cm) that resulted in a higher intensity burn with substantial mortality of pole and overstory trees (Bradley *et al.* 2006).

Table 1. Number of plots and units per treatment and vegetation type.

Vegetation Type		Treatment Type					
		Control	Hand-thin	Mast	Mast + Burn	Burn Only	Total
Chaparral	Unit	5	6	8	8	6	34
	Plot	10	10	16	16	12	64
Oak	Unit	11	11	10	11	10	53
	Plot	22	22	20	22	20	106
Total	Unit	16	16	19	19	16	87
	Plot	32	32	36	38	32	170

Plots were established in 2004 after treatments were applied. The southwest corner of each treatment unit was designated a coordinate (0 m, 0 m) and a random number generator was used to determine the x-y coordinates that were used to establish the location of two plots within each unit. These coordinates, in addition to the dimensions of the plot, were later used to determine the distance from the edge of the plot. Within each plot, fuel and vegetation data were collected. Initial data collection included litter depth, vegetation cover, ground cover, and canopy cover. Monitoring was conducted 1 to 3 years after treatment, but only year 2 was used for this study because it consisted of a complete data set. Plots were remeasured in 2018 and additional fuel transects and shrub belt transects were established.

Within each plot, a belt transect was established from the center and base of the vegetation plot extending 3 m east and 2 m north to estimate live shrub density and height for all shrub species (Figure 2). Shrub height was recorded for up to 10 individuals of each species within each belt transect and all shrubs were tallied by species. The average height was calculated and the total number of live shrubs per transect were used to calculate live shrub density (# stems/m^2).

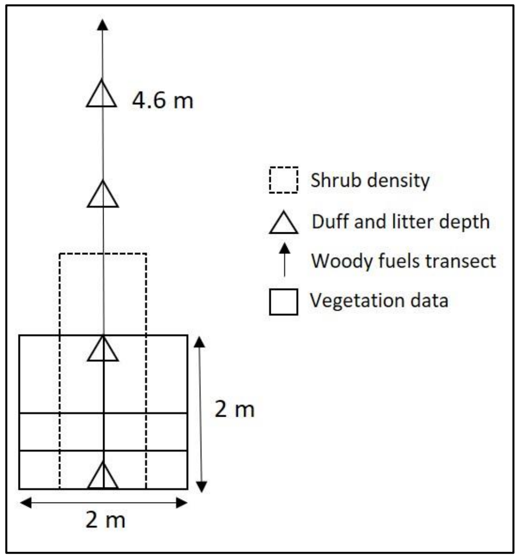


Figure 2. Plot design for fuel and vegetation field data collection.

I established a fuels transect to quantify fuelbed depth and dead woody fuel loading. The fuels transect was 4.57 m long and started at the base of the plot and ran through the center of each of the two vegetation plots per unit. Four duff and litter fuel depth measurements were taken at 0, 1.83, 3.66 and 4.57 m along the transect. Woody fuel loading was quantified and calculated using the planar intercept method and was modified to include dead branches still attached to rooted shrubs (Brown 1974). One-hour fuels (woody material with a diameter less than 6.35 mm), and ten-hour fuels (woody material with a diameter between 6.35 mm to 25.4 mm) were tallied along the first 1.83 m of the fuels transect. One hundred-hour fuels (woody material with a diameter between 2.54 and 7.62 cm) were tallied along the first 3.66 m of the transect.

Thousand-hour fuels (with a diameter of greater than or equal to 7.62 cm) were examined along the entire transect. For each 1,000-hr fuel that crossed the transect, we recorded the species, decay status (sound or rotten), diameter at both ends, and length.

I used Equation 1 to calculate the slope correction factor (*c*) and Equation 2 to calculate fine woody fuel loading by timelag class (1-hr to 100-hr). The count of downed woody material is signified by *n*. The midpoint of the diameter (*d*) range was used to characterize particle sizes for 1-, 10-, and 100-hr fuel (3.18 mm, 9.53 mm, and 2.54 cm, respectively) and by taking the average of the two measured end diameters of 1000-hr fuels that intercepted the transect. Specific gravity (*s*) values was 0.48 for both 1- and 10-fuel and 0.40 for 100-hr fuel. Non-horizontal correction factor (*a*) for 1 to 100-hr timelag classes was 1.13. Values for *s* and *a* used in our calculations were provided by Brown (1974). Transect length (*l*) was 1.83 m for both 1- and 10-hr fuels and 3.66 m for 100-hr fuels. Equation 3 was used to estimate 1000-hr fuel loading. For Equation 3, *d* is the average diameter, c was measured using Equation 1, *s* = 0.4 for sound and 0.3 for rotten, *a* = 1, and *l* = 4.57 m (Brown 1974).

Equation 1: $c = \sqrt{}(1 - \left(\frac{Percent\ slope}{100}\right)^2)$

Equation 2: $Fuel\ load\ (\frac{kg}{m^2}) = \frac{(1.234 \times n \times d^2 \times s \times a \times c)}{l}$

Equation 3: $Fuel\ load\ (\frac{kg}{m^2}) = \frac{(1.234 \times \sum d^2 \times s \times a \times c)}{l}$

For understory vegetation monitoring, a 1 m × 2 m quadrat was used to visually estimate ground cover, such as litter, bare ground, and vegetation cover, using six Daubenmire (1959) cover classes (0 = 0%; 1 = <1 to 5%; 2 = 6 to 25%; 3 = 26 to 50%; 4 = 51 to 75%; 5 = 76 to 95%; 6 = 96 to 100%). The quadrat was broken up into four 0.5 m × 1 m and cover values were recorded in each. The mid-point of each cover class was taken and averaged per quadrat. Understory vegetation was identified and recorded at the species level using local plant lists and collections, the Plants database (USDA 2018), and the Jepson Manual (Greenhouse *et al.* 2012). Each species was assigned a cover value using the same cover classes described above. Shrub and tree canopy cover were quantified using a densiometer, which was held at hip level over the center of the vegetation plot. Percent cover was calculated as the proportion of 96 points intersected by vegetative cover. Four measures were taken in each cardinal direction, averaged and multiplied by 1.04 (Lemmon 1956).

Statistical Analysis

Fuels data were analyzed at the block level ($n = 10$). The mean and standard error of the fuelbed depth, fuel loading by timelag class were calculated for each treatment. No further statistical analysis was conducted for duff or 1,000-hr fuel loading because it was not a major component of my study site. Based on the non-normal distribution of the remaining fuels data (live shrub height, live shrub density and woody fuel loading), I analyzed the data using a generalized linear model assuming a gamma distribution with a log link function with the *glmm* package (Knudson *et al.* 2018) in R (R Development

Core Team 2018). Vegetation type was considered in all model comparisons. Treatment was included as the predictor variable for live shrub height, shrub density and woody fuel loading with timelag as an additional variable. Live shrub cover was analyzed using a weighted generalized linear model of the binomial family with the logit function. This logistic regression used the proportion of cover values between 0 – 1 with a weight of 1 representing the maximum total cover possible. The effect of treatment, time, and their interaction were tested for litter depth using a generalized linear model in the gamma distribution family with the log link function. Litter depth was the only fuel response variable to include time as a factor because data were collected in both 2005 and 2018.

Vegetation cover data were summed by origin (native or exotic) for each plot. Mean cover per plot was analyzed at the block level (n=10) using the same weighted generalized linear model as described above for the analysis of live shrub cover. Species richness was calculated as the number of species per 1 m × 2 m quadrat and was analyzed using a linear mixed effects model with the *lme4* package (Bates *et al.* 2019) in R because the count data was normally distributed. Block and unit were included as nested random effects. Edge effect was considered for species richness by including a linear regression of shortest distance from edge (x), by species richness (y). Because there was no significant correlation found ($t = -1.88$, $P = 0.06$), it was not considered in the model. The relationship of litter depth and canopy cover with species richness was separately analyzed using a generalized linear model in the gamma distribution family with a log link function because the data was not normally distributed. Predictor variables in the species richness and cover for the understory vegetation models included treatment, time since treatment, and the interaction of treatment and time since treatment. I used Akaike Information Criteria (AIC) for all model comparisons to select the simplest and most explanatory models based on the model having the lowest AIC value with > 2 units difference from all other models.

The understory plant community response to fuels treatments between the two time periods was visualized using non-metric multidimensional scaling (NMDS) ordination with the *vegan* package (Oksanen *et al.* 2018) in R. This method takes a multi-variate non-parametric dataset and condenses it to a number of axes depending on the stress level, or how well the output represents the data. I chose to use three dimensions to ensure a satisfactory stress level (< 0.2) and used Jaccard distance measures to get axis scores (McCune and Grace 2002). Ordinations were completed using percent cover data for species that occurred in at least 5% of all plots and the abundances were standardized by taking the square root to eliminate rare species and account for relative plant abundance. Environmental variables such as litter cover, canopy cover and slope were tested to see how strongly correlated the factors were to axes scores of composition and were overlaid as joint plots. Separate permutational multivariate analysis of variance (perMANOVA) tests were done using the adonis function in the *vegan* package for oak and chaparral vegetation types to determine if dissimilarity indices differed by treatment, time, and the interaction of treatment and time. Lastly, an indicator species analysis was conducted using the *indicspecies* package (De Cáceres 2013) in R to see if species of particular interest (rare or exotic) were associated with treatments. The indicator species analysis used the community matrix of all the plots and the abundance of all species that occurred in at least 5% of all plots to test for species specifically and predominantly found in a treatment type. The p-value is the probability a plant is found in a treatment due to chance and the Indicator Value (IV) is the product of the specificity and fidelity.

RESULTS

Fuels

A treatment effect of live and dead fuel components compared to the control remained after 15 years, yet varied widely among treatments. Vegetation type did not improve any of the live and dead fuel models. All fuels treatments had a lower shrub height compared to the control ($t < -2.0$, $P < 0.001$), except for the spring burn treatment ($t = -1.48$, $P = 0.15$; Table 2, Figure 3). The shrubs in the control and Burn Only treatment stood the tallest (127.4 ± 22.99 to 165.1 ± 20.89 cm) and the other treatments were 31.1 to 51.3% shorter. Live shrub density in the Mast + Burn treatment was 2.3 times greater than the control ($t = 3.38$, $P < 0.001$, Table 2, Figure 3). All treatments increased in live shrub cover from 2 to 15 years after treatment, but had no statistical significance. Shrub cover was consistently the lowest on average in the Mast treatment (from 7.3 to 20.7%), while the Mast + Burn had the greatest increase over time (from 13.4 to 40.0%) (Figure 4).

The tall shrubs in the control and spring treatment contained dead woody surface fuels that contributed 27.7% of the fine woody surface fuels (1 to 100-hr) in the control and 32.0% in the Burn Only. The total fine dead woody fuel loading (1-hr to 100-hr) 15 years after treatment was lower within the Hand-thin ($t = -5.32$, $P < 0.001$) and Mast + Burn ($t = -3.85$, $P < 0.001$; Figure 5, Table 2) treatments compared to the control. For

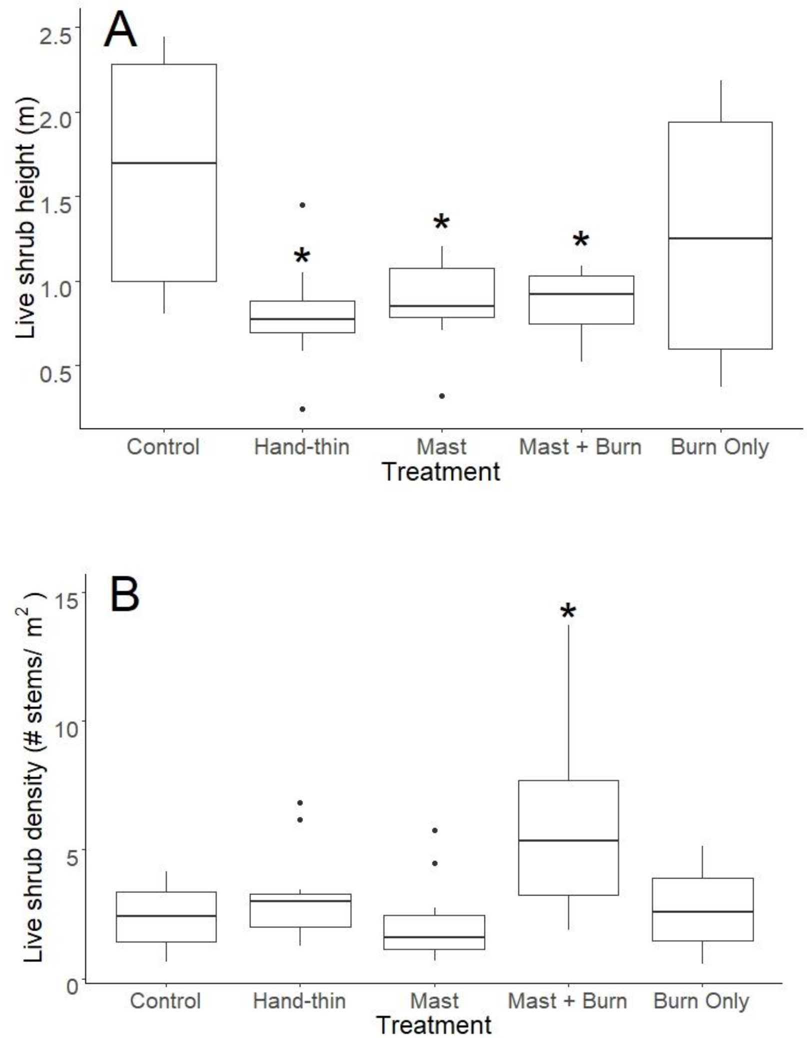


Figure 3. Live shrub height (m) (A), and live shrub density (# stems/m^2) (B), across all treatments and control 15 years after treatment. The asterisks denote significant differences from the control resulting from a generalized linear model (* < 0.001).

these two treatments, fuel loading was 1.8 to 3.0 times less for 10-hour fuels, and 1.5 to 3.0 times less for 100-hour fuels compared to the other treatments and the control. Litter depth was reduced initially in Mast ($t = -2.42$, $P = 0.02$) and Mast + Burn ($t = -3.45$, $P = 0.001$) treatments, but both increased to control levels after 15 years (Figure 6).

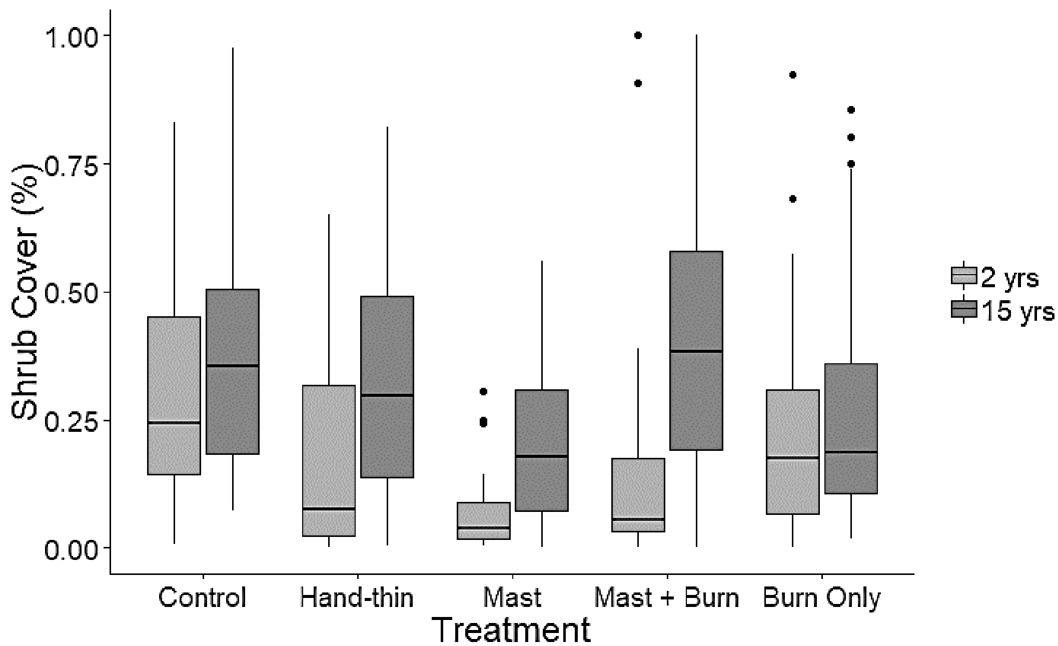
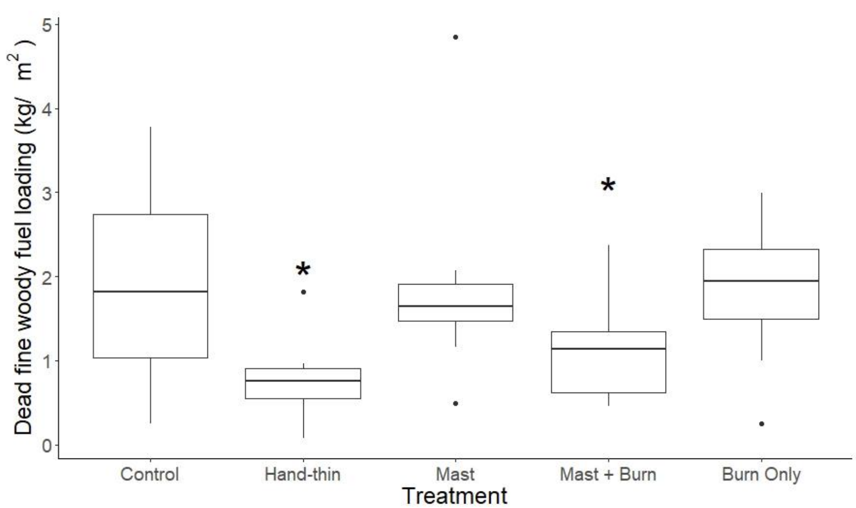


Figure 4. Shrub cover (%) across all treatment and control 2 and 15 years after treatment.

Figure 5. Dead fine woody (1 to 100-hr) fuel loading (kg/m^2) across all treatments and



control 15 years after treatment. The asterisks denote significant differences from the control resulting from a generalized linear model (* < 0.001).

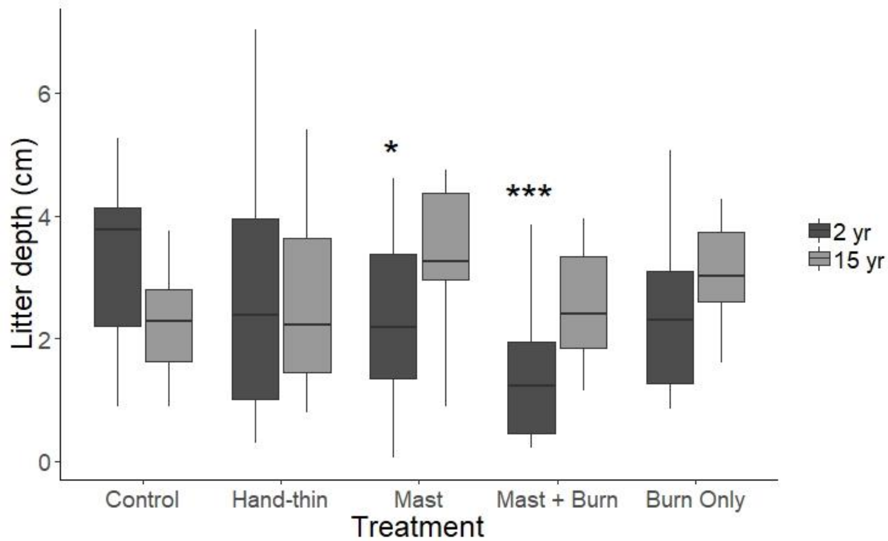


Figure 6. Litter depth in (cm) between all treatments and the control 2 years and 15 years after treatment. The asterisks denote significant differences from the control and time periods resulting from a generalized linear model (*** < 0.001, * < 0.05).

Table 2. Surface fuel characteristics (mean ± SE) 15 years after fuel treatments in chaparral and oak woodland. The asterisks denote the levels of significant difference compared to the control based on a generalized linear model (*** < 0.001, ** < 0.01, * < 0.05).

Variable	**Treatment**	**Control**	**Hand-thin**	**Mast**	**Mast + Burn**	**Burn Only**
Fuelbed depth						
(cm)	Duff	0.7 (0.26)	0.3 (0.15)	0.7 (0.24)	0.2 (0.08)	0.8 (0.27)
	Litter	2.3 (0.27)	2.6 (0.48)	3.4 (0.36)	2.6 (0.30)	3.1 (0.28)
	Fuelbed	3.0 (0.45)	2.9 (0.58)	4.0 (0.56)	2.7 (0.35)	3.9 (0.51)
Dead fuel load						
(kg/m^2)	1-hr	0.1 (0.02)	0.1 (0.01)	0.1 (0.01)	0.1 (0.01)	0.1 (0.02)
	10-hr	0.9 (0.17)	0.3 (0.05)	0.9 (0.16)	0.5 (0.08)	0.9 (0.17)
	100-hr	0.9 (0.26)	0.3 (0.12)	0.9 (0.22)	0.6 (0.18)	0.9 (0.21)
	Fine woody					
	(1-100-hr)	1.2 (0.39)	0.7 (0.15) ***	1.9 (0.36)	1.2 (0.19) ***	1.8 (0.25)
	1,000-hr	11.0 (5.48)	9.6 (3.80)	11.0 (4.06)	30.8 (13.82)	4.6 (2.36)
Live shrub fuels						
	Density (# / m^2)	2.4 (0.34)	3.0 (0.50)	2.0 (0.4)	5.7 (1.07) ***	2.6 (0.48)
	Height (cm)	1.7 (0.21)	0.8 (0.1) ***	0.9 (0.1) ***	0.9 (0.06) ***	1.3 (0.23)
	Cover (%)	0.4 (0.04)	0.3 (0.05)	0.2 (0.03)	0.4 (0.05)	0.3 (0.06)

Vegetation

Across both monitoring time periods, a total of 113 species were identified including 89 native and 24 exotic species. Of these species, 10 were trees, 15 shrubs, 22 grasses, and 66 forbs. Treatment type and time since treatment influenced species richness. Species richness in the Mast + Burn treatment was initially 20.0 to 27.7% greater than all other treatments ($t = 5.11$, $P < 0.001$) and the control, but was made up of ~30% exotic species. Time was a significant factor in total species richness as there were 19.4% more species 2 years compared to 15 years after treatment ($t = 5.99$, $P < 0.001$). Across all treatments, 19.6% more exotic and 19.1% more native species occurred two years compared to 15 years after treatment (Table 3). Initial increases in species richness were associated with treatments that reduced litter depth ($t = -3.86$, $P < 0.001$; Figure 7), but was not associated with changes in shrub cover ($t = -0.002$, $P = 0.27$).

There was no effect of treatment or time on plant cover ($P > 0.05$). Although not statistically significant, there was a higher cover of exotic plants in the treated versus untreated units and exotic plant cover increased over time (Figure 8). Based on the indicator species analysis, there was an exotic grass associated with the Mast treatment and the Mast + Burn treatment. Exotic grass *Vulpia bromoides* was associated with the Mast treatment (IV = 0.36, $P = 0.003$), and *Vulpia myuros* was associated with the Mast + Burn treatment (IV = 0.45, $P = 0.034$).

Table 3. Species richness (mean ± SE) as number of species per 1 m × 2 m quadrat by origin (native and exotic), 2 and 15 years after fuel treatments in chaparral and oak woodland. A significant effect of time was found for total species richness, with more species 2 years after treatment and decreasing over time ($P < 0.001$).

Treatment		**Control**		**Hand-thin**		**Mast**		**Mast + Burn**		**Burn Only**	
Origin	**Time**	**2 yrs**	**15 yrs**	**2 yrs**	**15 yrs**	**2 yrs**	**15 yrs**	**2 yrs**	**15 yrs**	**2 yrs**	**15 yrs**
Native		6.1	5.1	6.5	5.6	6.0	4.7	6.7	5.0	6.6	5.4
		(0.48)	(0.45)	(0.71)	(0.56)	(0.63)	(0.74)	(0.75)	(0.57)	(0.78)	(0.84)
Exotic		1.2	1.4	1.9	1.3	1.6	1.4	2.9	2.2	1.6	1.1
		(0.33)	(0.31)	(0.33)	(0.35)	(0.38)	(0.36)	(0.47)	(0.39)	(0.35)	(0.36)
Total		6.8	5.9	8.1	6.8	7.2	5.7	9.4	7.1	7.7	6.1
		(0.65)	(0.69)	(0.86)	(0.83)	(0.87)	(0.89)	(1.13)	(0.91)	(0.98)	(0.93)

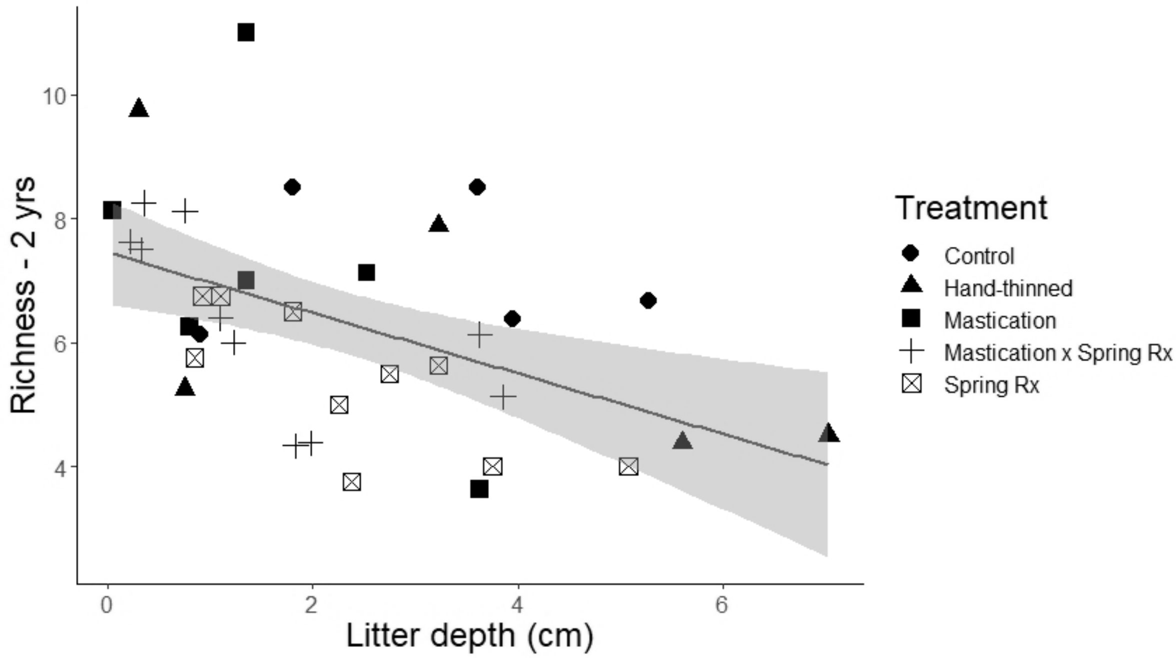


Figure 7. Mean species richness per 1 m × 2 m quadrat two years post treatment as a function of litter depth (cm) with 95% confidence intervals from a generalized linear regression (r^2 =-0.483; p<0.02).

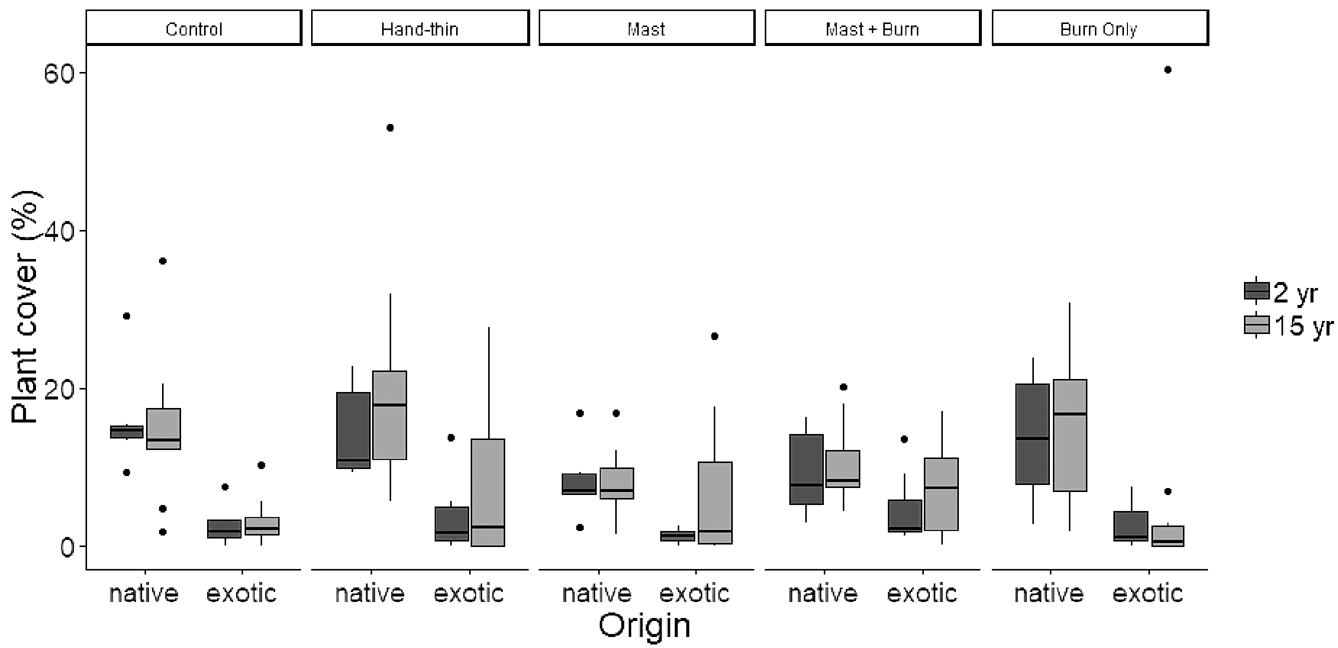


Figure 8. Percent cover of understory plants by treatment and origin (native/exotic) 2 and 15 years after treatment.

Differences in plant community composition were associated with treatment and time since treatment. Non-metric multidimential scaling produced a three-dimensional solution with a stress value of 0.19 (19%) for the chaparral- and oak-dominated sites. For the chaparral-dominated sites, Axis 1 explained 25.8%, Axis 2 explained 7.3%, and Axis 3 explained 8.6% of the variation. In the oak dominated sites, Axis 1 explained 15.6%, Axis 2 explained 10.7%, and Axis 3 explained 10.7% of the variation. Community composition differed by treatment type in the chaparral-dominated ($F_{103,4}$ = 1.84, P = 0.005) and the oak-dominated sites ($F_{171,4}$ = 2.46, P = 0.005), as well as time since treatment in both chaparral ($F_{103,1}$ = 4.87, P = 0.005) and oak-dominated ($F_{171,1}$ = 4.46, P = 0.005) sites. There was a significant interaction of treatment type and time since treatment on composition in chaparral sites ($F_{103,4}$ = 1.40, P = 0.02) but not in the oak sites ($F_{171,4}$ = 1.21, P = 0.10). Time had a relatively greater effect on composition based on the F values. Plant composition in the chaparral vegetation type was correlated with litter cover (Axis 1, r^2 = 0.34, P = 0.001) and canopy cover (Axis 2, r^2 = 0.10, P = 0.007). Plant composition in the oak vegetation types was correlated with litter cover (Axis 1, r^2 = 0.15, P = 0.001), canopy cover (Axis 2, r^2 = 0.07, P = 0.002), and slope (Axis 1, r^2 = 0.06, P = 0.006). In both vegetation types, species composition shifted over time with increased litter and canopy cover.

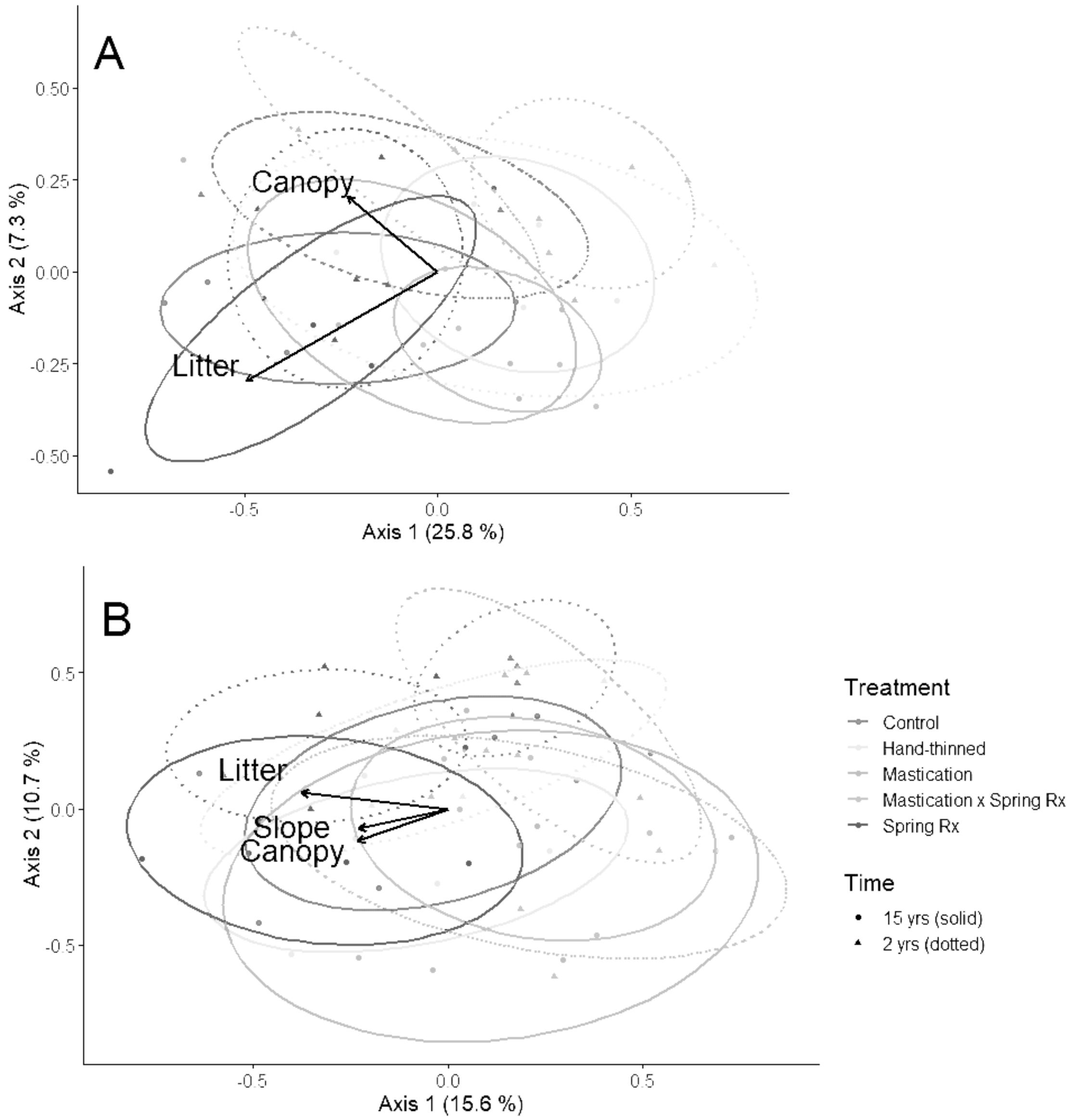


Figure 9. Chaparral-dominated (A) and oak-dominated (B) plant community analysis using percent cover values for each vegetation plot two years after treatment (dotted lines) and 15 years after treatment (solid lines) for each treatment type. Positional results were calculated using the non-metric multi-dimensional scaling ordination method. Significant environmental variables ($P < 0.05$) are represented by joint plots (black arrows) for litter cover (%), canopy cover (%) and slope (°).

DISCUSSION

Overall, the effectiveness of fuel treatments in northern chaparral and oak stands from both a fuels and understory plant community perspective varied widely, but some treatments clearly differed in ways that can be useful for planning and management decisions. The long-term effectiveness of fuels treatments was mostly driven by the degree to which shrub fuels were reduced or inhibited. All treatments except the Burn Only treatment were highly effective in reducing shrub height compared to the control even after 15 years. However, the Mast + Burn treatment resulted in a significant increase in the shrub density that will eventually reach pre-treatment levels. The Burn Only treatment failed to reduce shrub height and, while it killed many of the shrubs, it generated substantial dead fuels that were elevated from the surface, the combination of which will likely contribute to substantial fire behavior if burned. Both the Hand-thin and Mast treatments were most effective in reducing shrub height and limiting the reestablishment of shrub fuel beds that should reduce potential fire behavior. Broadly, fuel treatments did not substantially impact the understory plant community. Mast + Burn treatments initially increased species richness but this effect was not detected over the long-term. However, there are some lingering concerns regarding the potential of fuel treatments to promote exotic species. While we did not find differences in exotic species cover among treatments, many had relatively high levels of exotic cover that could pose problems if another exposed to another disturbance in the near future. In addition, an exotic grass species that is a known facilitate type conversion in chaparral was strongly associated with the Mast + Burn treatment.

Shrubs are the main component of chaparral ecosystems and the primary driver of fire behavior due to high fuel loads, fuelbed depths, and continuity that contribute to higher fire intensity and rapid fire spread. Thus, in order to be effective in the long-term, treatments must reduce shrub fuels and limit shrub recovery (Brennan and Keeley 2015). My results support previous studies in that mechanical treatments had a slower rate of shrub recovery than the use of fire alone (Potts *et al.* 2009; Wilken *et al.* 2017) or when combined with mechanical treatments (Brennan and Keeley 2015). The mastication treatment inhibited the propagation by seed due to the mulch produced from fuel treatment and the lack of fire stimulation. The consumption of the litter bed and stimulation of shrub seed germination led to a profound increase in live shrub fuels in the combined Mast + Burn in my study, and was consistent with that found by Kane *et al.* (2010), making this treatment less effective in reducing live shrubs compared to other treatments. While the shrub height in the Mast + Burn treatment was significantly reduced, the resultant increase in shrub regeneration will decrease the effectiveness over time. Assuming a steady rate of growth in shrub height, I estimate that shrubs in the Mast + Burn treatment will reach control levels in approximately 30 years after treatment. Consistent with the findings of Brennan and Keeley (2015), mechanical treatments had ~30% less shrub cover compared to the combined Mast + Burn. However my study spanned almost twice the length of time, showing an extended longevity in the effectiveness of the mastication only treatment through live shrub fuel reduction and inhibition of regeneration. Another study in northern California chaparral showed that mastication was slightly more effective than fire at reducing shrub cover over the long-term, with shrub cover reaching within 8% of pre-treatment levels after ten years in masticated sites (Wilken *et al.* 2017). However, Wilken *et al.* (2017) had much greater shrub cover values than in my study and Brennan and Keeley (2015), likely due to a higher proportion of resprouting species at their sites. The Burn Only treatment was not effective in reducing live shrubs in my study, but was an effective treatment in others, at least in the short-term. Both Potts *et al.* (2009) and Wilkin *et al.* (2017) found initial reductions in shrub cover compared to the control from the use of fire alone, but still had higher shrub cover than mastication only sites ten years after treatment. The differences in shrub cover response to prescribed fire alone treatments observed between these studies is likely due to substantial differences in fire behavior that was generated.

In my study, the Burn Only treatment was the least effective at decreasing dead fuels due to low fire intensity and poor fuel consumption under high moisture conditions. Retention of shrubs that provided ample shading and reduced wind speeds in this treatment likely inhibited the drying rates of fuels prior to ignition. The low intensity of the prescribed fire was sufficient to kill a large proportion of the shrubs but was unable to consume the shrub fuels. Instead, this treatment resulted in an increase in fine woody fuel loading, many of which were often 1.5 m above the ground, creating hazardous ladder fuels, and increasing the potential fire behavior and risk of severe crown fire. While we did not have fine woody fuel data two years following treatment, we presume that shortly after the Burn Only treatment the amount of dead shrub fuels dramatically increased and that this increase persisted over time, elevating fire risk even after 15 years. The persistence of these fuels over time suggests much slower decomposition rates than surface fuels in contact with the ground (Barber and Van Leer 1984). There was also a substantial amount of dead shrub fuels in the control, likely due to self-thinning and pruning over time. In this case, the risk of severe fire would likely increase because of the amount of dead shrub fuels present. However, the rate of recruitment of dead shrub fuels was likely much slower than the Burn Only treatment.

The Mast treatment did not reduce fine woody fuel load compared to the control 15 years after treatment. While fine woody fuels have not decreased compared to the control, a portion of the initial fuels generated after mastication seem to have decomposed. Within the same study site three years after the mastication only treatment, Kane et al. (2009) estimated fine woody fuel loading was 20.4 Mg/ha which was slightly higher than the current estimate of 18.6 Mg/ha. In a subsequent study that examined fuel loading at the same study site 9 years later, Reed (2016) found that fine woody fuels decreased by 43 to 75% depending on the timelag class.

The Mast treatment also has the potential for intense fire behavior in masticated fuel beds when applying prescribed fire shortly following mastication, resulting in high flame lengths and prolonged smoldering times that can increase tree mortality and decrease control capabilities (Bradley *et al.* 2006; Knapp *et al.* 2011; Kreye *et al.* 2014). The increased intensity and severity in mastication treatments could occur during a wildfire as well. However, this risk would decrease over time with the decomposition of the mastication material as described above (Brennan and Keeley 2015). In the Mast +

Burn treatment, the risk of severe fire from increased woody surface fuel load was reduced immediately and remained reduced 15 years later.

The Hand-thin treatment was one of the most effective treatments because of its clear reduction in shrub height and additional decreases in dead woody fuels, all of which persisted after 15 years. The initial effectiveness of this treatment was garnered by the physical removal of shrubs that were later burned in piles off site. Shrub height was initially reduced by hand-thinning in a previous study (Kane *et al.* 2010), but this study did not find reduced dead woody fuels in the Hand-thin treatment. The lack of a seed germination response of shrubs contributed to the increased longevity of this treatment. Additional reductions in dead surface fuel loading may have been gained due to increased light exposure that could have accelerated decomposition. While this treatment was highly effective, other considerations, such as cost and time, may pose limitations in its wider application.

The understory plant response to fuel treatments had subtle differences among treatments and greater differences over time. From 2 to 15 years after all treatments, there was a decrease in native species richness and a shift in community composition, both associated with increased litter depth. The accumulation of litter over time likely inhibited seed germination and reduced conditions that were suitable for further establishment and growth of understory vegetation. Increased species richness following the Mast + Burn treatment in my study was consistent with Kane *et al.* (2010), though this increase also included exotic species. Potts and Stephens (2009) found greater species richness in mastication treatments compared to spring burning treatments, but at the expense of increased exotic species richness as well. Two other studies in northern California chaparral found no significant treatment effect on species richness, although they did find an increase in the number of exotics (Perchemlides *et al.* 2008; Potts *et al.* 2009).

Vulipa myuros was strongly associated with the Mast + Burn treatment in my study. This species is known to contribute to type converting shrublands to exotic grasslands, and historically was intentionally used to facilitate type conversion (Howard 2006). Although not statistically significant, my data showed an increase in exotic plant cover over time following treatment. The association of *V. myuros* to the Mast + Burn treatment aligns with the concerns expressed over frequent disturbance leading to type conversion from shrubland to annual grasslands (Brennan and Keeley 2012). While the impact of treatments on exotic species cover is highly varied, most studies have demonstrated the substantial presence of exotic species that may pose future problems of expansion and risks of type conversion if the frequency of disturbances (e.g. treatment or wildfire) increases.

These results indicate most fuel treatments will involve some potential tradeoffs between reducing fuels and maintaining the ecological integrity of chaparral communities. While the native plant community thrives following severe crown fire (Barro and Conrad 1991; Keeley and Fotheringham 2001), these fires can pose substantial risks to surrounding human communities (Syphard *et al.* 2014). Fuel treatments that are effective in altering fuels to reduce potential fire behavior in chaparral stands also have the potential to promote the expansion of exotic plant species (Keeley

2007). Other studies (Wilken *et al*. 2017; Potts and Stephens 2009) recommend prescribed fire as a treatment to reduce fuel loading while limiting the risk of exotics. This recommendation may be applicable to chaparral stands that experience higher intensity prescribed burns and contain rapid resprouters. However, the Burn Only treatment in my study mostly contained the obligate seeder *A. viscida* that died following the application of a low intensity prescribed fire and likely increased fire risk because of the increased dead shrub component. A follow up prescribed burn could be an appropriate option in reducing fuels generated by low intensity burning, while potentially reducing the risk of exotics. On the other hand, this repeated fire could lead to increased exotics with a heightened vulnerability to type conversion (Brennan and Keeley 2012). Further research is needed to examine the potential impacts of repeated prescribed burns in chaparral as a treatment option. In my study, the Hand-thin and Mast treatments most effectively reduced live shrub fuels over the long-term, largely due to its ability to reduce shrubs and limit recovery compared to the other treatments. These two treatments could be appropriate options for fuel reduction when higher intensity prescribed fire is not feasible. The Mast + Burn treatment effectively reduced dead fuels but increased live shrub fuels at a greater rate than the other treatments.

While my study examined changes to fuel structure to assess the potential long-term effectiveness of treatments, examining the fire behavior and effects of these treatments following wildfire would provide a much better assessment of effectiveness. Given the increase in frequency of large fires throughout the region over the past few decades (Westerling 2016), it is increasing more possible that wildfires could affect a recently treated area. In fact, shortly after field data was collected for this study in 2018 the Carr Fire burned through our entire research site. This coincident occurrence provides a more direct means of examining the long-term effectiveness of these fuels treatments that will be evaluated as part of a future study. The treatment site could potentially experience a difference in fire severity or lead to different responses of shrub regeneration and understory plant composition, especially exotic species. Depending on treatment type at my study site, a subsequent wildfire would be the first to third disturbance experienced within 16 years. The presence of different treatments that contained a range of entries provides a unique opportunity to examine the potential impacts to understory plant responses to the combination of treatments and wildfire that can add additional information to influence management decisions.

In conclusion, fuel treatment can effectively reduce fuel loading and/or structure after 15 years. The Burn Only treatment resulted in many outcomes that are often counter to management objectives because of the substantial increase in dead surface fuels that have the potential to increase the risk of severe fire, both over the short- and long-term. The remaining fuel treatments in this study had tradeoffs between live and dead fuel load and structure and the native plant community. This study provides land managers with more information to enhance treatment effectiveness to reduce the risk of severe fire in northern California chaparral from both a fuels and ecological perspective.

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