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Fuel accumulation and forest structure change following hazardous fuel reduction treatments throughout California

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Abstract. Altered fuel conditions coupled with changing climate have disrupted fire regimes of forests historically characterised by high-frequency and low-to-moderate-severity fire. Managers use fuel treatments to abate undesirable fire behaviour and effects. Short-term effectiveness of fuel treatments to alter fire behaviour and effects is well documented; however, long-term effectiveness is not well known. We evaluated surface fuel load, vegetation cover and forest structure before and after mechanical and fire-only treatments over 8 years across 11 National Forests in California. Eight years post treatment, total surface fuel load returned to 67 to 79% and 55 to 103% of pretreatment levels following fire-only and mechanical treatments respectively. Herbaceous or shrub cover exceeded pretreatment levels two-thirds of the time 8 years after treatment. Fire-only treatments warranted re-entry at 8 years post treatment owing to the accumulation of live and dead fuels and minimal impact on canopy bulk density. In general, mechanical treatments were more effective at reducing canopy bulk density and initially increasing canopy base height than prescribed fire. However, elevated surface fuel loads, canopy base height reductions in later years and lack of restoration of fire as an ecological process suggest that including prescribed fire would be beneficial.

Additional keywords: dry mixed conifer, mechanical treatments, moist mixed conifer, prescribed fire, yellow pine.

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Introduction

Fire has been a part of California's ecosystems for thousands of years (Sugihara *et al.* 2006). Throughout the western United States, fire exclusion, timber harvesting, livestock grazing, mining and settlement have altered forest structure. Today, forests are characterised by smaller trees, higher vegetation density and higher fuel loads than in the past (Agee and Skinner 2005). The transformation of fuel conditions, coupled with a changing climate, has altered the fire regime in coniferous forests typified by historically high-frequency and low-to-moderate-severity fires (e.g. Westerling *et al.* 2006; Miller *et al.* 2009; Mallek *et al.* 2013; Stephens *et al.* 2013; Safford and Van de Water 2014). In California, a recent analysis of fire return interval departure found low- and middle-elevation dry coniferous forests to be the most departed, meaning they have missed multiple fire cycles (Safford and Van de Water 2014). In addition, when wildfires occur in these systems, they now often burn over a larger extent and at a higher severity than in the past (Miller *et al.* 2009; Mallek *et al.* 2013).

Under the guidance of the National Fire Plan and the 10-Year Comprehensive Strategy (USDA-USDI 2001), the use of fuel treatments to reduce the likelihood of catastrophic or uncharacteristic fires (Hardy 2005) has increased over the past decade. The FLAME Act of 2009 and resulting National Cohesive Wildland Fire Management Strategy ('Cohesive Strategy') re-iterate the need to revisit wildland fire management in the US (Lee *et al.* 2011). One of the three core goals of the Cohesive Strategy is to restore and maintain fire-resilient landscapes (Wildland Fire Leadership Council (WFLC) 2014). It is not possible to fire-proof forests, and the effectiveness of treatments is determined by a combination of the treatment itself, the behaviour of the approaching fire, climatic conditions and the level of fire suppression actions taken (Agee and Skinner 2005; Reinhardt *et al.* 2008). Fuel treatments are typically designed to reduce or redistribute ground, surface and canopy fuels to slow the spread of fire, reduce the intensity of fire, and reduce the likelihood of crown fire. Although reducing the rate of fire spread is a primary target, the final fire size can be less important than reducing fire intensity, and therefore fire effects (Reinhardt *et al.* 2008).

Fuel treatments have a finite life span that will depend on the conditions before treatment, the effectiveness of the treatment itself and the productivity of the vegetation (Reinhardt *et al.* 2008). The short-term effectiveness (1 to 2 years) of fuel treatments to abate undesirable fire behaviour and effects is well studied and known in dry coniferous systems (e.g. Stephens and Moghaddas 2005; Reiner *et al.* 2009; Stephens *et al.* 2009; Vaillant *et al.* 2009*a*, 2009*b*; Fulé *et al.* 2012; McIver *et al.* 2012; Safford *et al.* 2012). Fire-only treatments generally reduce undesired future fire behaviour by consuming ground, surface and live understorey fuel loads, while moderately affecting canopy fuels (e.g. Stephens and Moghaddas 2005; Stephens *et al.* 2009; Vaillant *et al.* 2009*b*; McIver *et al.* 2012). Mechanical-only treatments, such as tree thinning followed by mastication, have mixed impacts on fuels and therefore predicted fire behaviour (Stephens and Moghaddas 2005; Reiner *et al.* 2009; Stephens *et al.* 2009; Vaillant *et al.* 2009*a*). However, tree canopy fuel reduction alone may reduce crown fire potential but not direct and indirect fire effects such as tree mortality resulting from increased surface fire intensity (Fettig *et al.* 2010; Martinson and Omi 2013). Treatments that include both mechanical methods and prescribed fire are the most effective in the short term (e.g. Stephens *et al.* 2009; McIver *et al.* 2012).

The long-term effectiveness of fuel treatments is not as well known. It has been hypothesised that forests will accumulate uncharacteristically high fuel loads if not treated within a period equal to twice the historic fire return interval (Caprio *et al.* 2002; North *et al.* 2012). In 12 wildfires in yellow pine and mixed-conifer forests of California, Safford *et al.* (2012) found no significant difference in fire severity or tree mortality between treatments ranging from 1 to 9 years old. Collins *et al.* (2009) reported that at least 9 years need to have passed before previously burned areas will reburn in wildfires in Yosemite National Park, which is close to the historic fire return interval. Ultimately, the longevity of fuel treatment effectiveness to reduce fire behaviour and effects will depend largely on the accumulation rates and distribution of fuels.

Very few studies quantify the effects of fuel treatments on fuel accumulation and forest structure beyond the first couple of years (van Wagtendonk and Sydoriak 1987; Keifer *et al.* 2006; Chiono *et al.* 2012; Stephens *et al.* 2012). In Yosemite, Sequoia and Kings Canyon National Parks, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forest floor and surface fuel loads returned to >50% the pre-prescribed burn levels within 5 years, up to 84% by 10 years, and 150 to 180% 31 years after initial treatment (Keifer *et al.* 2006). In a mixed-conifer forest in the central Sierra Nevada, initial reductions in forest floor and surface fuel loads from fire-only treatments started to recover to ~50% of pretreatment after 7 years (Stephens *et al.* 2012). Mechanical treatments in mixed-conifer and Jeffrey pine (*Pinus jeffreyi* Balf.) stands of the Sierra Nevada produced variable changes to fuel loads over time (Chiono *et al.* 2012; Stephens *et al.* 2012). Mixed-conifer stands maintained lower forest floor and surface fuel loads than Jeffrey pine stands, which recovered close to untreated levels in stands treated more than 8 years prior (Chiono *et al.* 2012). Relative to untreated controls, reduced canopy bulk density, canopy cover, basal area and increased canopy base height were maintained 7 or more years after mechanical treatment (Chiono *et al.* 2012; Stephens *et al.* 2012).

With the current backlog of federal lands requiring treatment in California, some suggest a two to five times increased intensity in annual fuel reduction treatments (North *et al.* 2012). Knowing the impact of fuel treatments on fuel accumulation and forest stand structure beyond an initial post-treatment assessment is necessary to better estimate fuel treatment longevity, and therefore retreatment intervals to maintain effectiveness. In this study, we quantified fuel treatment effects on forest floor (litter and duff), dead and downed surface fuels, understorey vegetation cover, and changes to forest stand characteristics before and up to 8 years after both mechanical and fire-only treatments within conifer forests of California.

Materials and methods

Fuel treatments

The data used in this study were from a regional monitoring program designed to characterise pre- and post-treatment fuels and vegetation as a result of management on National Forests in California. This study includes 19 fuel treatments conducted by 11 National Forests (Inyo (INF), Klamath (KNF), Lake Tahoe Basin Management Unit (TMU), Lassen (LNF), Modoc (MDF), Mendocino (MNF), Plumas (PNF), San Bernardino (BDF), Shasta-Trinity (SHF), Stanislaus (STF) and Tahoe (TNF); Fig. 1). Fuel treatments were grouped into two types: fire-only and mechanical. The 12 fire-only treatments were burned with

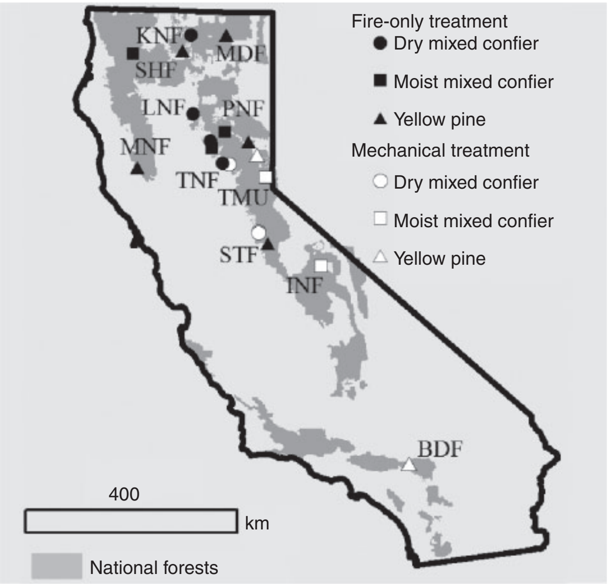

Fig. 1. Fuel treatment project locations by treatment type and presettlement fire regime (PFR). For a description of the PFRs and forest codes please refer to the text.

broadcast prescribed fire. The seven mechanical treatments included a tree-thinning treatment followed by a surface fuel treatment. The surface fuel treatments included: mastication or chipping of downed woody material, understorey vegetation and small-diameter trees (two fuel treatments), on-site hand or machine piling of materials that were burned (two fuel treatments), or offsite biomass removal (three fuel treatments). Owing to a lack of sufficient replicates across the range of post-thinning surface fuel treatments, they were combined into one mechanical category.

Due to the geographic range of this research, each fuel treatment project was assigned a presettlement fire regime (PFR) based on location for analysis (Van de Water and Safford 2011; Fig. 1). Twenty-eight PFR types were mapped within California; each was derived from current vegetation type, consultation with fire and vegetation ecologists in California and published data. Our plots fall geographically within three PFRs: dry mixed conifer, moist mixed conifer and yellow pine (Table 1). Dry mixed-conifer PFR is dominated by ponderosa pine, sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* (Torr.) Florin), white fir (*Abies concolor* (Gord. & Glend.) Lindl ex Hildebr.) and California black oak (*Quercus kelloggii* Newberry) with a median fire return interval (MFRI) of 9 years (Van de Water and Safford 2011). Moist mixed-conifer PFR is dominated by white fir, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense cedar, ponderosa pine, sugar pine and lodgepole pine (*P. contorta* Douglas ex Louden) with an MFRI of 12 years (Van de Water and Safford 2011). Yellow pine PFR is dominated by ponderosa pine, Jeffrey pine, sugar pine and California black oak with an MFRI of 7 years (Van de Water and Safford 2011).

Field sampling

Up to six plots were randomly located within each fuel treatment project before the treatment occurred. The six plots included 'detailed' and 'fuels' plots. The detailed plots included data collection on forest floor and surface fuels, understorey vegetation and trees, whereas the fuels plots did not include tree data (except canopy cover). The field sampling protocol was based on the National Park Service Fire Monitoring Handbook (USDI National Park Service 2003) with some modifications to optimise sampling efficiency (Vaillant *et al.* 2009*a*). Field sampling occurred at four time intervals: all plots were sampled before treatment, then 1, 2 and 8 years post treatment.

Table 1. Sample size by treatment type, presettlement fire regime, project and plot type
Please refer to the text for plot type descriptions

Treatment type	Pre-settlement fire regime	Project	Fuels plot	Detailed plot
Fire-only	Dry mixed conifer	4	9	7
	Moist mixed conifer	3	7	6
	Yellow pine	5	12	12
Mechanical	Dry mixed conifer	3	7	6
	Moist mixed conifer	2	5	2
	Yellow pine	2	7	6

Overstorey and pole-size tree information was gathered within fixed-area nested plots, sized 0.1 and 0.025 ha respectively. Overstorey trees included those $\geq$15 cm diameter at breast height (DBH); pole-sized trees were $\geq$2.5 and $<$15 cm DBH. For all live trees, tag number, species, DBH, height to live crown base and total height were recorded. For all dead trees, tag number, species, DBH and total height were recorded.

Understorey vegetation and tree canopy cover data were collected along 50-m transect(s). Shrub data included: species, intercept length along each transect and vigour (live or dead). Species, vigour and estimates by cover class (Daubenmire 1959) were recorded for subshrubs, herbs and grasses (hereafter collectively referred to as 'herbaceous') within five 1 by 1-m quadrats placed every 10 m along each transect. Tree canopy cover was measured every metre along each transect using a sight tube.

Litter, duff and dead and downed woody material were inventoried following the planar intercept method (Brown 1974; Van Wagner 1968) with 15.24-m transects. Dead and downed 1-h ($\leq$0.64 cm in diameter) and 10-h (0.64 to $\leq$2.54 cm in diameter), and 100-h (2.54 to $\leq$7.62 cm in diameter) fuels were tallied for the first 1.83 and 3.66 m respectively. Diameter and species were recorded for all dead and down 1000-h fuels ($>$7.62 cm in diameter) along the entire transect. Litter and duff depths were recorded at 10 equidistant points along each transect starting at 0.3 m. Surface fuel and forest floor loads were directly calculated from field data coefficients specific to the Sierra Nevada range (van Wagtendonk *et al.* 1996, 1998).

Calculating stand characteristics

The Fire and Fuels Extension (FFE-FVS, Reinhardt and Crookston 2003; Rebain 2010) for the Forest Vegetation Simulator (FVS, Crookston and Dixon 2005) was used to calculate tree density, canopy bulk density and canopy base height. The FVS is a stand-level distance-independent forest growth and treatment model used to support management decisions based on field-collected data. The FFE-FVS leverages tree growth from FVS, and models non-tree fuel loads (i.e. accumulation and decomposition of dead woody material) over time, models potential fire behaviour, and calculates carbon stocks. The FVS and FFE-FVS use geographically derived equations called 'variants' to model tree growth and fuel accumulation and decomposition over time. Our plots are within four variants: western Sierras, southern Oregon–north-east California, Klamath Mountains, and Inland California–Southern Cascades.

Statistical analysis

We used a generalised linear mixed model (Proc GLIMMIX) with repeated-measures in *SAS 9.2*^{TM} (SAS Institutes Inc., Cary, NC) to analyse changes in fuel loads, vegetation cover and stand characteristics over time. The fuel treatment project and year were included as random factors in the model because plots within a project were not truly independent and treatment intervals occurred during different calendar years. Before statistics were run, a significance level of $P < 0.1$ was chosen because of the known spatial variability of fuels (Keane *et al.* 2012). For mechanical treatments in the moist mixed-conifer PFR, no statistics were completed for the stand characteristics because of the small sample size ($n = 2$). Results were summarised by PFR (dry mixed conifer, moist mixed conifer, yellow pine) and treatment type (fire-only and mechanical) for time periods: pretreatment (P0), 1 year after treatment (P1), 2 years after treatment (P2), and 8 years after treatment (P8).

Results

Fuel loads

For fire-only treatments, litter and duff, 1-h and 10-h fuel loads were significantly reduced the year following treatment for all PFRs, and remained lower through P8. The exception was 10-h fuels in yellow pine where the reduction was not significant from treatment and P8 exceeded P0 (Fig. 2). Although not significant, fire tended to reduce 100-h and 1000-h fuel loads (i.e. P1 was less than P0), and remained lower through P8. The one exception was 1000-h fuels in dry mixed conifer, but there was no trend over time (Fig. 2).

For mechanically treated sites, there were no apparent trends in fuel loads through time (i.e. peak 1-h fuel load occurred in P1 for dry mixed conifer and P2 for moist mixed conifer and yellow pine; Fig. 3). For all but two instances (dry mixed conifer 1000-h and moist mixed conifer 100-h), either or both P1 and P2 exceeded P0 for all the dead and down woody fuel classes, with the increase being significant only one-third of the time (Fig. 3). By P8, average fuel loads were generally lower than the peak loading; however, although not significant, only one-third were lower than P0. The exceptions were litter and duff in dry mixed-conifer forests and 1000-h fuel in yellow pine.

Vegetation cover

Herbaceous cover was reduced for all PFRs the year following treatment relative to pretreatment, except for dry mixed conifer treated with fire, which increased by 5% (Figs 4, 5). The reduction ranged from 43 to 85%, with only those in yellow pine being significant (Figs 4, 5). Herbaceous cover was significantly higher P8 than P0 in the dry mixed-conifer PFR for fire (almost double) and mechanical (more than triple) treatments.

Shrub cover was lowest at P1 for all PFRs for both treatments and continued to increase from P2 to P8 (Figs 4, 5). By P8, shrub cover exceeded P0 cover for dry mixed conifer and yellow pine for both fire-only (582 and 159% respectively) and mechanical (390 and 165% respectively) treatments.

For the fire-only treatment, reductions in tree canopy cover were minimal (<12% between P0 and P1) and stable over time (Fig. 4). Mechanical treatments significantly reduced tree canopy cover (P0 versus P1) for all PFRs (Fig. 5). In the mechanical

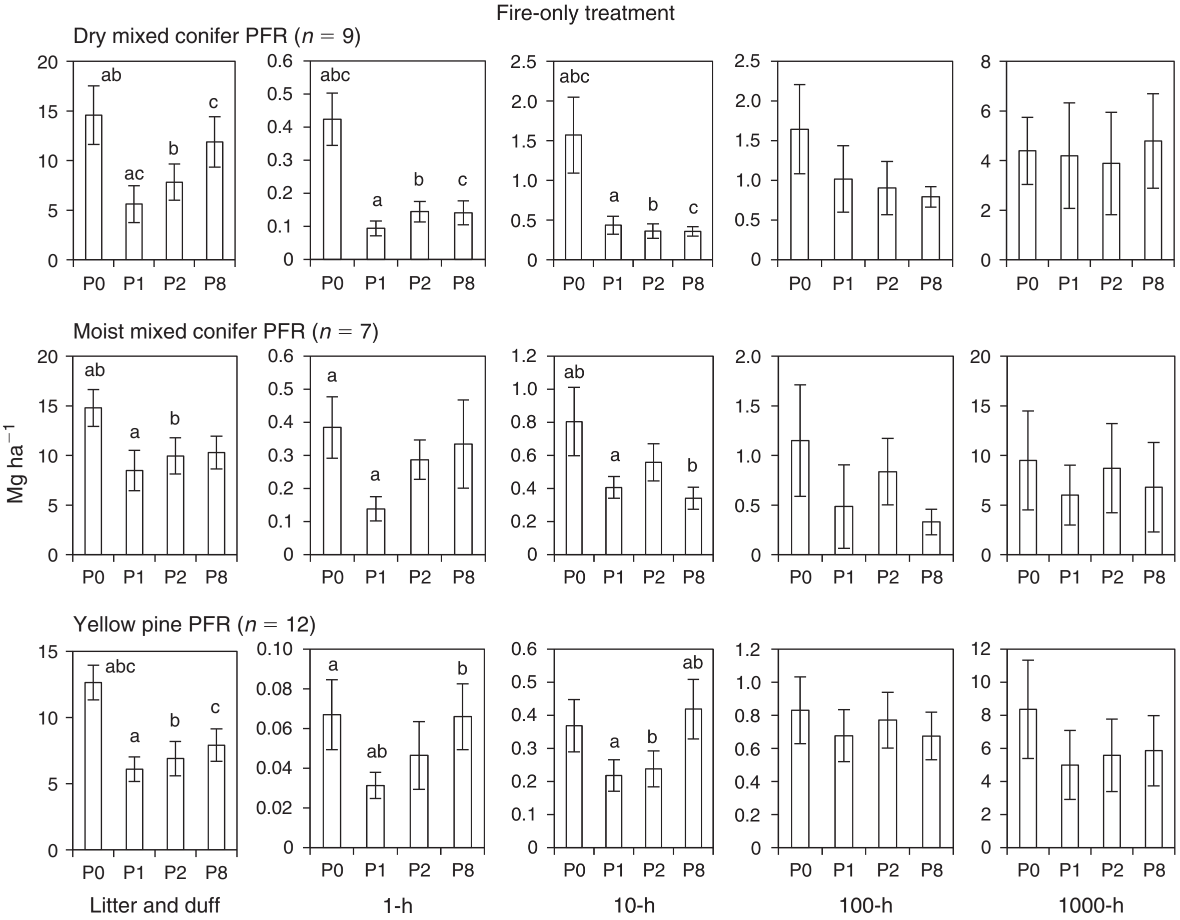

Fig. 2. Mean (±s.e.) fuel loads by class (litter and duff, 1-h, 10-h, 100-h, 1000-h), presettlement fire regime (PFR) type and time period for fire-only treatment. Bars with the same letter are significantly different for those time periods for each fuel load class and PFR type.

treatments from P1 through P8, tree canopy cover steadily increased but remained lower than P0, with only yellow pine being significantly lower at P8 than P0 (Fig. 5).

Stand characteristics

In general, fire-only and mechanical treatments both reduced average canopy bulk density and overstorey and pole-sized tree density and increased canopy base height (Figs 6, 7). In dry mixed conifer and yellow pine, mechanical treatments reduced canopy bulk density by 30 and 47% and remained significantly lower than P0 for P1, P2 and P8 (Fig. 7). Prescribed fire did not significantly affect canopy bulk density, but it was reduced 12 to 18% by P2 and remained lower at P8 than P0 for all PFRs (Fig. 6). Initial lifts in canopy base height following treatments (P1 and P2 relative to P0) started to decline by P8 but remained equal to or higher than P0 (Figs 6, 7). Changes to canopy base height in fire-only treatments were only significant in yellow pine, where P2 and P8 were both higher than P0 and P1 (Fig. 6). Changes to canopy base height were not significant for mechanical treatments; however, by P2, canopy base height was 85 to 230% higher than P0 (Fig. 7).

Over time, live tree density declined after prescribed fire, except for pole-sized trees for dry mixed conifer where P8 density was higher than prior time periods' (Fig. 6). In dry mixed conifer and yellow pine, mechanical treatments significantly reduced the number of overstorey trees (P0 versus P1), then density remained steady (<2% change between P1, P2 and P8) and significantly lower than P0 (Fig. 7). Mechanical treatments reduced pole-size tree density >50% in dry mixed conifer, 100% in moist mixed conifer and 90% in yellow pine between P0 and P1 (Fig. 7). However, the number of pole-sized trees more than doubled in yellow pine between P2 and P8.

Dead tree density of both tree classes in dry and moist mixed conifer treated by fire increased through P2 and then decreased in P8, indicating that they began to fall over (Fig. 6). In yellow pine, pole-sized dead trees followed the same trend as mixed conifer. In contrast, overstorey dead trees did not exceed P0 until P2 and continued to increase through P8. Dead tree density was reduced in mechanical treatments for overstorey and pole-sized trees in dry and moist mixed conifer between P0 and P1, and continued to decline through P8 where dead trees still existed (Fig. 7). Dead tree density was very low in yellow pine before mechanical treatment (less than 2 dead trees ha^{-1} for both tree size classes combined for each time period) and remained relatively unchanged.

Discussion

Of the 19 fuel treatment sites included in this study, only four experienced a wildfire since the early 1900s, and those same sites

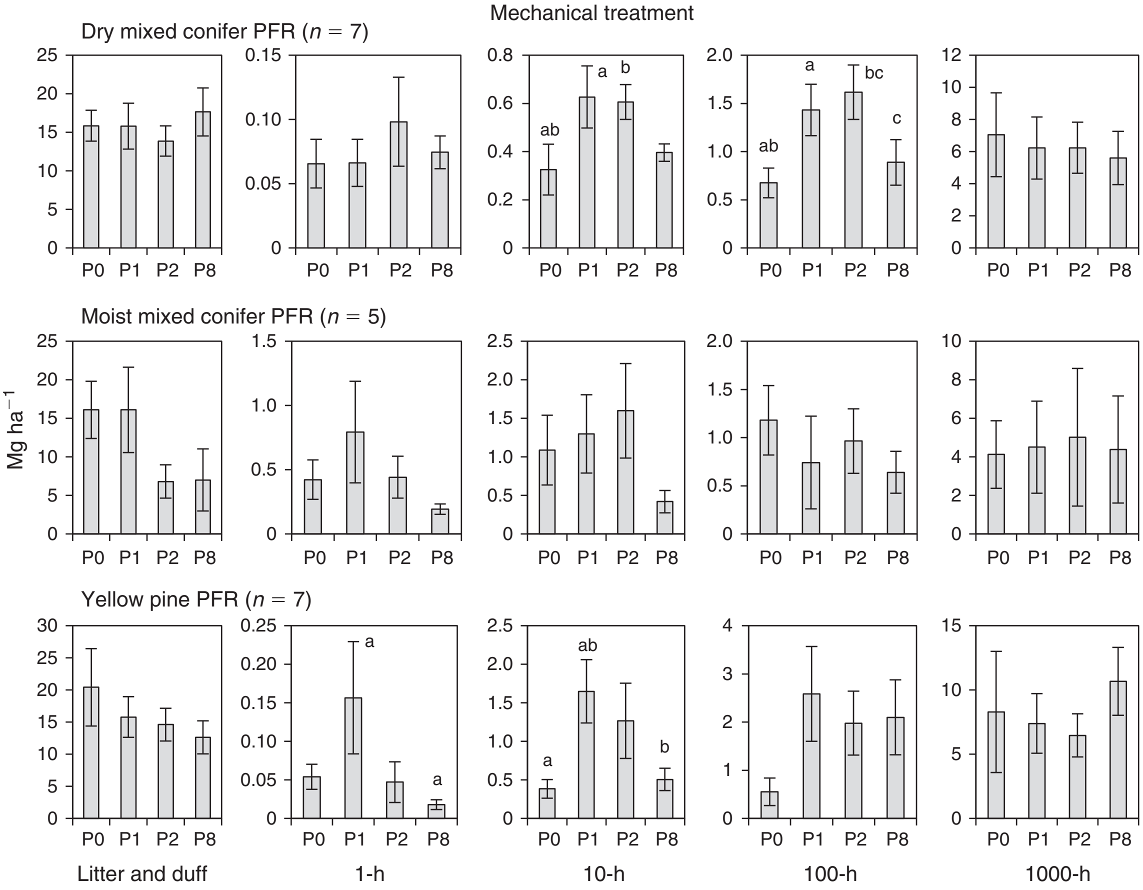

Fig. 3. Mean (±s.e.) fuel loads by class (litter and duff, 1-h, 10-h, 100-h, 1000-h), presettlement fire regime (PFR) type and time period for mechanical treatment. Bars with the same letter are significantly different for those time periods for each fuel load class and PFR type.

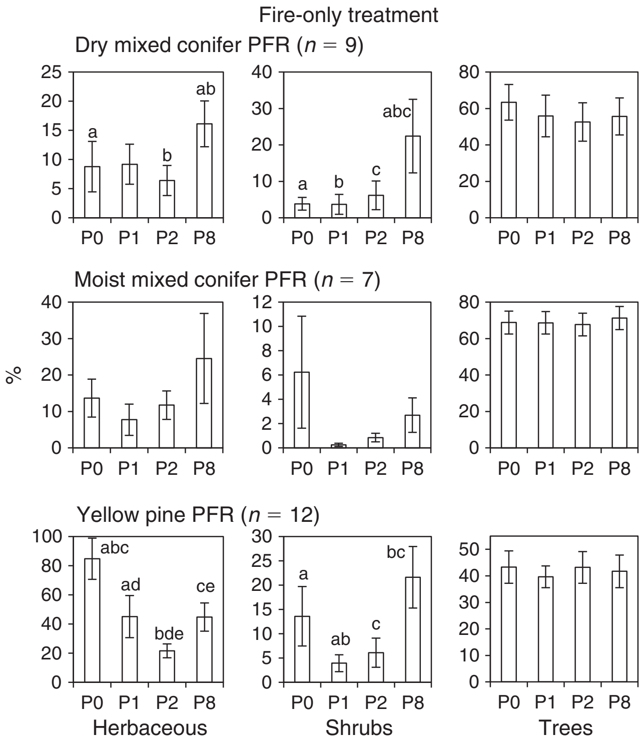

Fig. 4. Mean (±s.e.) vegetation cover by type (herbaceous, shrub, tree), presettlement fire regime (PFR) type and time period for fire-only treatment. Bars with the same letter are significantly different for those time periods for each cover and PFR type.

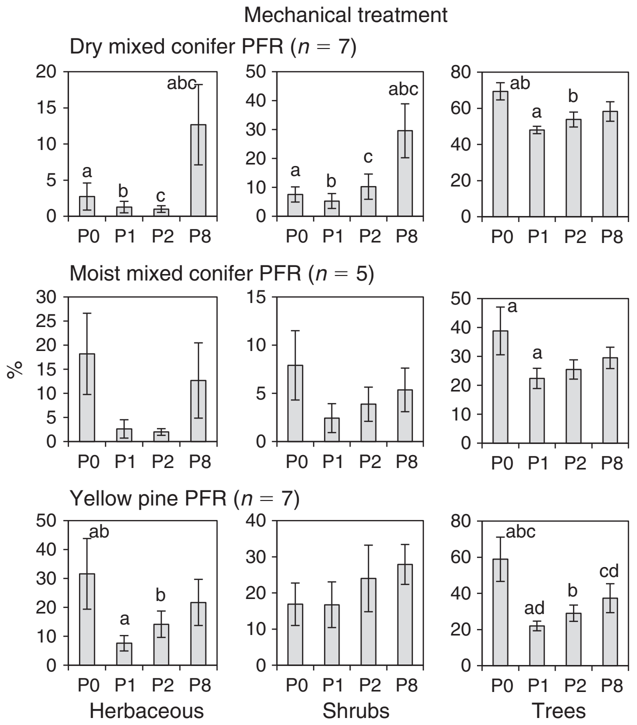

Fig. 5. Mean (±s.e.) vegetation cover by type (herbaceous, shrub, tree), presettlement fire regime (PFR) type and time period for mechanical treatment. Bars with the same letter are significantly different for those time periods for each cover and PFR type.

have missed at least five rotations (based on the MFRI), indicating they have all highly departed from the historic fire regime. This is typical of many of the dry forest types in California (Safford and Van de Water 2014), which have uncharacteristically high fuel loads (Caprio *et al.* 2002; North *et al.* 2012). Trends in fuel accumulation rates can help managers predict the effective duration of fuel treatments and plan retreatment intervals (van Wagtendonk and Sydoriak 1987). Very few studies have quantified the extended effects of fuel treatments on fuel accumulation (van Wagtendonk and Sydoriak 1987; Keifer *et al.* 2006; Chiono *et al.* 2012; Stephens *et al.* 2012). Keifer *et al.* (2006) determined that total fuel load (litter and duff plus dead and downed surface fuels) returned to ~85% of pretreatment levels 10 years after fire-only treatments in ponderosa pine and mixed-conifer forests of the southern Sierra Nevada. Seven years after prescribed fire in a northern Sierra Nevada mixed-conifer forest, Stephens *et al.* (2012) found total fuel load had accumulated to ~50% of pretreatment. Our findings were intermediate between Keifer *et al.* (2006) and Stephens *et al.* (2012). By P8, we found the total fuel load returned to 67 to 79% of P0. Similarly to van Wagtendonk and Sydoriak (1987), we found litter and duff and 1-h fuels accumulated more rapidly in the first 2 years after prescribed fire (from P1 to P2) than in later years, which would be expected as scorched needles and fire-killed smaller-diameter branches rapidly fall to the forest floor. After 2 years, dead trees started to fall (Fig. 6); however, this was not captured well in the 1000-h fuel class dataset (Fig. 2) because the fallen trees rarely intersected the fuels transects.

Chiono *et al.* (2012) retrospectively quantified fuel loads and forest stand metrics from fuel treatments in mixed-conifer and Jeffrey pine forest types in the Sierra Nevada in untreated and treated stands 2 to 4 years, 5 to 7 years, and ≥8 years after treatment. Treatments included thinning alone or in combination with prescribed fire, making direct comparisons with our work difficult. Interestingly, the inclusion of multiple time steps in Chiono *et al.* (2012) highlighted the variability in fuel load with respect to time since treatment, which we also found. Part of this variability is likely due to the lumping of mechanical treatment types into a single category for both our work and Chiono *et al.* (2012). Although mechanical treatments included one of three different surface fuel treatments (i.e. mastication, piling, or offsite biomass removal), the effects were similar to those reported by Stephens *et al.* (2012) for mechanical-only treatments in mixed conifer where the secondary treatment was mastication. Both the research presented here and Stephens *et al.* (2012) report increased fine dead woody (1- to 100-h fuel) loads at P1 relative to P0. Seven years after treatment, Stephens *et al.* (2012) observed fine dead woody fuel load returned to near pretreatment levels. In contrast, we observed higher fine dead woody fuel loads in dry mixed conifer, but levels were ~50% of pretreatment levels for moist mixed conifer. Coarse (1000-h) fuels were not immediately affected by mechanical-only treatment in Stephens *et al.* (2012), but were reduced 7 years after treatment. In our study, mean coarse fuel load remained consistent over time (<20% change) in dry and moist mixed-conifer PFRs (Fig. 3).

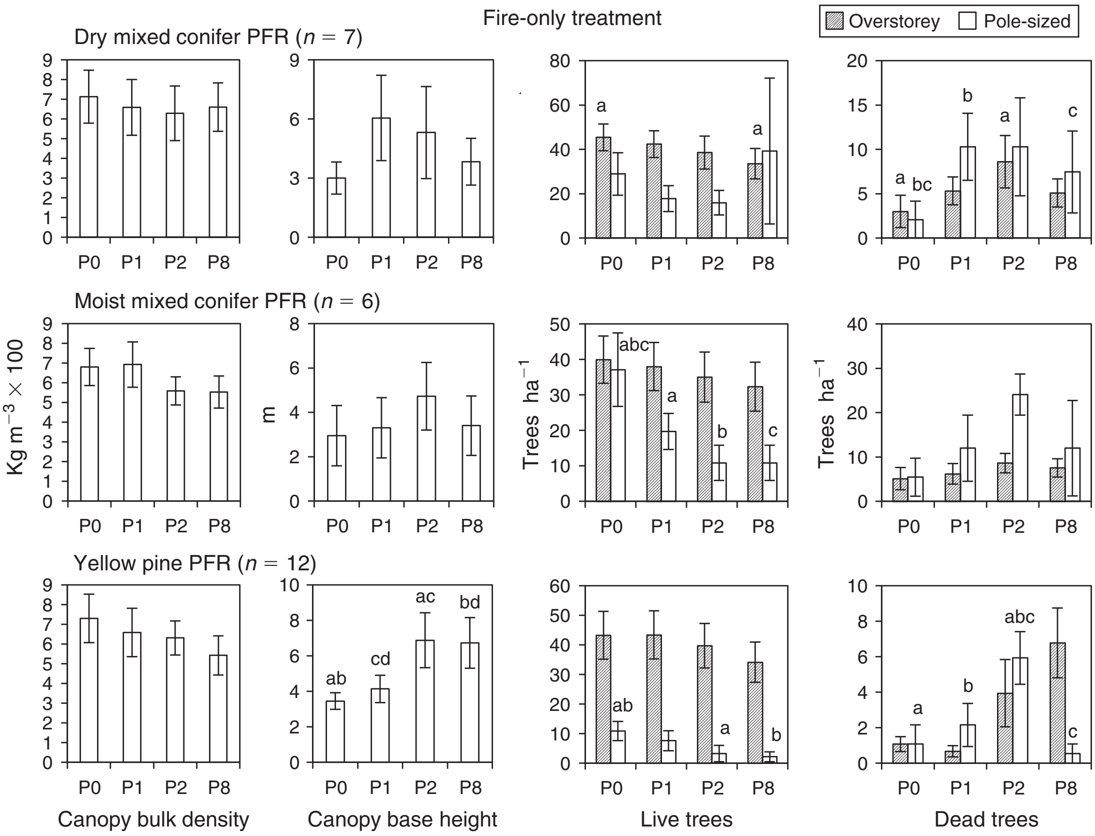

Fig. 6. Mean (±s.e.) stand characteristics (canopy bulk density, canopy base height, live and dead tree density) by presettlement fire regime (PFR) type and time period for fire-only treatment. Bars with the same letter are significantly different for those time periods for each cover and PFR type.

Understorey vegetation responses are likely linked to pretreatment conditions (Fulé *et al.* 2005). In our sites, dry mixed conifer had the lowest pretreatment herbaceous cover whereas yellow pine had the highest. The percentage increase at P8 relative to P0 was directly related to pretreatment cover, with the lowest pretreatment cover groupings having the highest post-treatment recruitment percentages. Unlike the herbaceous cover, pretreatment shrub cover did not dictate post-treatment cover recovery; however, the drier PFRs (yellow pine and dry mixed conifer) exceed pretreatment shrub cover by P8, whereas moist mixed conifer did not. Changes in understorey plant composition and cover can affect potential fire spread in multiple ways. Treatments may result in increased growth of grasses and understorey shrubs, which can increase surface fire rates of spread (Reinhardt *et al.* 2008). Increases in live shrub cover may also dampen fire spread because shrubs tend to cure more slowly than herbaceous fuels (Korb *et al.* 2007) or may shade surface fuels, resulting in higher moisture content (Kauffman and Martin 1989). The ratio of dead to live foliage in shrubs can also affect fire spread, with the decrease of the ratio from the removal of dead branch wood and new growth after treatment, ultimately slowing spread. Increases in both herbaceous plant and shrub cover can contribute to ladder fuels and crown fire potential.

A primary goal of fuel treatments is to reduce the likelihood of crown fire behaviour. The initiation of crown fire is a function of the surface fire intensity, canopy base height and foliar moisture (Van Wagner 1977; Alexander 1988; Scott and Reinhardt 2001). In 61 plots within experimental fires, Cruz *et al.* (2004) found when the gap between the top of the fuel bed and base of live ladder and canopy fuels (i.e. fuel strata gap) is less than 2 m, initiation of crown fire activity is common, and above 7 m, the likelihood is greatly reduced. We acknowledge that the thresholds developed by Cruz *et al.* (2004) were for forest types more typical of Canada and will potentially be different for the forest types we sampled in California. However, this generalised risk analysis does allow an effectiveness assessment of treatments over time to reduce the potential for crown fire initiation. Using the thresholds found by Cruz *et al.* (2004), before treatment, 40% of the fire-only and 57% of the mechanical plots were at high risk (fuel strata gap $<$ 2 m), and 4% of the fire-only and 14% of the mechanical plots were very low risk ($>$7 m) for crown fire initiation. Treatment increased the number of prescribed fire plots at very low risk to 24% in P1 and 35% by P2, and stayed constant through P8, indicating continued resistance to crown fire initiation over the observed period. Mechanical treatment increased plots at very low risk to 36% in P1, but by P2 it reduced them to 29% and also remained unchanged through P8. Treatment reduced plots at high risk for crown fire initiation to 24 and 23% for fire-only and mechanical treatments respectively. However, by P8, 32% of the fire-only and 50% of the mechanical plots returned to high risk.

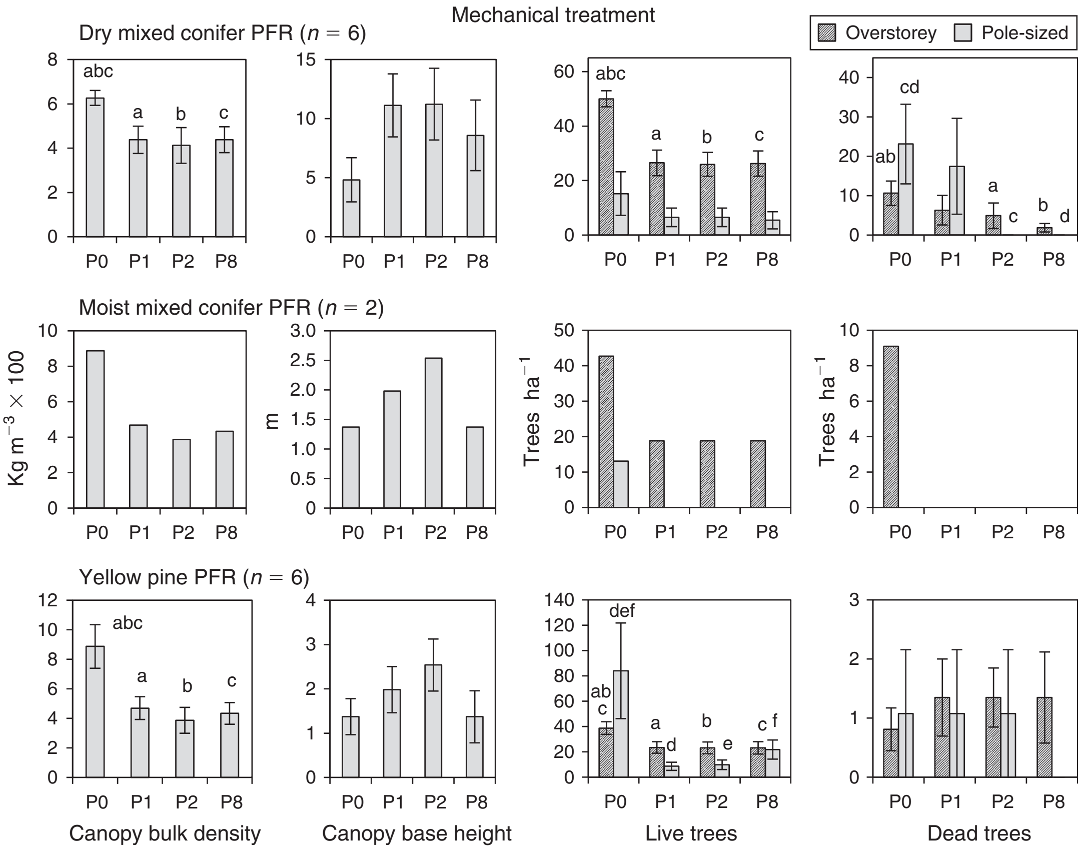

Fig. 7. Mean (±s.e.) stand characteristics (canopy bulk density, canopy base height, live and dead tree density) by presettlement fire regime (PFR) type and time period for mechanical treatment. Bars with the same letter are significantly different for those time periods for each cover and PFR type. Because of the low sample size, s.e. and statistics were not completed for the moist mixed-conifer PFR.

Stands with a canopy bulk density greater than 0.1 kg m^{-3} are more likely to sustain active crown fire once it is initiated (Agee 1996). Prior to treatment, only 16% of the plots treated mechanically exceeded this threshold and after treatment, only one plot remained above 0.1 kg m^{-3}. Prescribed fire reduced canopy bulk density, reducing the percentage of plots exceeding the threshold from 32% in P0 to 24%, 12% and 16% for P1, P2 and P8 respectively. Fire-only treatments further reduced canopy bulk density from P1 to P2 owing to the reduction of overstorey trees from delayed mortality, which was found in other mixed conifer forests in the Sierra Nevada (van Mantgem *et al.* 2011; Stephens *et al.* 2012). The increase in canopy bulk density at P8 was in dry mixed conifer and was likely from the infill of smaller trees (Fig. 6). With approximately three-quarters of the plots at moderate to high risk for crown fire initiation and 13% with potential for sustained crown fire 8 years after treatment, a maintenance entry at this time interval would be beneficial to increase the fuel strata gap and further reduce canopy bulk density (especially in fire-only treated plots).

A single treatment will not likely mitigate fuel accumulation and forest structure change resulting from fire exclusion and past management, which is the situation on the majority of our sites. Rather, higher-intensity fire or repeated management will be required on many sites to retain acceptable fuel loads and reduced tree density (Agee *et al.* 2000; Innes *et al.* 2006; Collins *et al.* 2010; Youngblood 2010; van Mantgem *et al.* 2011). Prior to treatment, our study sites had not burned in greater than twice the historic fire return interval; therefore, they were likely to have uncharacteristically high fuel loads before treatment (Caprio *et al.* 2002; North *et al.* 2012). Consistent with the MFRI (7 to 12 years depending on the PFR), total surface fuel load was on average 77% of P0 by P8 (range 55 to 103%) for both treatment types. The minimal impact of the prescribed burns on canopy bulk density and canopy cover, as well as the lowering of canopy base height over time, infill of smaller trees, and increases in understorey vegetation cover warrant re-entry with another treatment aimed at managing ladder and canopy fuels to mitigate crown fire risk. Mechanical treatments alone can restore forest structure; however, an application of fire is needed to restore ecological processes such as nutrient cycling and vegetation diversity (Fites-Kaufman *et al.* 2006; Wohlgemuth *et al.* 2006; Webster and Halpern 2010; North *et al.* 2012). Although the mechanical treatments were effective at reducing canopy bulk density and increasing canopy base height, the post-treatment variability of surface fuel loads especially in the larger size classes and lack of restoration of fire as an ecological process warrant a need for a prescribed fire treatment. The timing and exact prescription of retreatment will be a balance dependent on surface fuel accumulation, understorey vegetation recovery, tree regeneration rates and canopy fuels. For example, if ingrowth of small trees and shrubs is occurring, but surface fuels are still at a reduced level, managers may have to wait longer for surface fuels to accumulate for fire intensity to be adequate for desired ladder fuel mortality. On more productive sites, managers may have to treat earlier than 8 years or complete multiple treatments to avoid surface and ladder fuel build-up to mitigate the potential for undesirable fire behaviour and effects.

Monitoring is often neglected because of the expense, time and expertise required (DeLuca *et al.* 2010). Increased monitoring of fuel treatment effects is needed to better understand how fuel accumulates and forest structure changes over time (e.g. Evans *et al.* 2011; van Mantgem *et al.* 2011). With the exception of the National Park Service and few long-term programs such as this one in California, cohesive monitoring does not exist and needs to be implemented to determine treatment effectiveness (Hunter *et al.* 2007). Furthering the point, we found a lack of temporal trends with respect to fuel loads and stand structure after mechanical treatment, similarly to other studies. This emphasises the need for expanded and consistent monitoring. The recently initiated Forest Service Collaborative Forest Landscape Restoration Program funds fuel treatment projects to re-establish natural fire regimes and reduce the risk of undesirable fires. The program requires monitoring social, ecological and economic outcomes for at least 15 years after implementation (Schultz *et al.* 2012, 2014). With no set monitoring protocol in place, and the program still relatively young and growing, it would be prudent to establish a cohesive methodology to ensure consistent and comparable monitoring data to evaluate management activities. The FFI (Feat/FIREMON Integrated) tool, a monitoring tool designed to assist with collection, storage and analysis of ecological data would be the perfect place to start (Lutes *et al.* 2009). Data from this research are archived in the FFI system.

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