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Effect of mastication and other mechanical treatments on fuel structure in chaparral

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Abstract. Mechanical fuel treatments are a common pre-fire strategy for reducing wildfire hazard that alters fuel structure by converting live canopy fuels to a compacted layer of dead surface fuels. Current knowledge concerning their effectiveness, however, comes primarily from forest-dominated ecosystems. Our objectives were to quantify and compare changes in shrub-dominated chaparral following crushing, mastication, re-mastication and mastication-plus-burning treatments, and to assess treatment longevity. Results from analysis of variance (ANOVA) identified significant differences in all fuel components by treatment type, vegetation type and time since treatment. Live woody fuel components of height, cover and mass were positively correlated with time since treatment, whereas downed woody fuel components were negatively correlated. Herbaceous fuels, conversely, were not correlated, and exhibited a 5-fold increase in cover across treatment types in comparison to controls. Average live woody fuel recovery was 50% across all treatment and vegetation types. Differences in recovery between time-since-treatment years 1–8 ranged from 32–65% and exhibited significant positive correlations with time since treatment. These results suggest that treatment effectiveness is short term due to the rapid regrowth of shrubs in these systems and is compromised by the substantial increase in herbaceous fuels. Consequences of not having a full understanding of these treatments are serious and leave concern for their widespread use on chaparral-dominated landscapes.

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Introduction

A major challenge facing land management agencies is how to manage wildlands in ways that minimise community vulnerability to wildfires while maintaining ecosystem processes to ensure their long-term sustainability. Nowhere is this problem more acute than in California, and particularly in the southern half of the state dominated by chaparral ecosystems prone to periodic high-intensity crown fires. Losses of property and lives due to fire in the urban environment of California greatly exceed that of any other region in the US (Miller 2007), putting intense pressure on managers to reduce fire hazard.

An important fire management strategy to reduce wildfire hazard is the use of pre-fire fuel manipulations or fuel treatments. In many parts of the western US, fuels management has relied heavily on the use of prescription burning (Agee and Skinner 2005). However, in crown fire ecosystems such as California chaparral, this is problematic because these landscapes are often in close proximity to high-density urban environments. Increasingly, fuels management has focussed on the use of mechanical treatments, including chipping, crushing, bulldozing, mowing and mastication to alter fuel structure (Agee and Skinner 2005). Data compiled from the USGS Southern California Fuel Treatment Data Set (http://www.cafiresci.org) show that since 2000, the number of these treatments on the four southern California national forests has risen exponentially, with mastication, crushing and chipping accounting for 40% of all combined fuel treatments conducted between 2000 and 2008. One advantage of using mechanical treatments is that they can be implemented at the wildland–urban interface and in areas where prescribed burning is difficult or not an option (Agee and Skinner 2005). These treatments are generally expected to alter fire behaviour by reducing flame lengths, intensity and rate of spread of fire (Hudak *et al.* 2011; Kreye *et al.* 2014*a*) through the relocation of fuels to densely compacted fuel beds at the ground surface (Stephens and Moghaddas 2005; Kane *et al.* 2009; Kreye *et al.* 2014*a*). This alteration of fuel structure potentially allows improved fire fighter access and suppression efficacy (Syphard *et al.* 2011). In many of the ecosystems where these mechanical treatments are employed, prescription burning is also utilised following treatment to reduce compacted fuel loads at the surface (Kane *et al.* 2010; Knapp *et al.* 2011).

An understanding of how fuel is altered within these compacted fuel beds is essential in order to model and better identify how treatments might affect fire behaviour. A common observation across initial studies characterising fuel loads in mechanically altered systems was that fuel loads were highly variable and that this variability could be partially attributed to pre-treatment site conditions, stand age, stand history, vegetation type, machinery used and desired post-treatment stand conditions (Stephens and Moghaddas 2005; Glitzenstien *et al.* 2006; Hood and Wu 2006; Kane *et al.* 2006, 2009; Schwilk *et al.* 2009; Battaglia *et al.* 2010; Kreye *et al.* 2014*a*).

The national Fire and Fire Surrogate (FFS) study was a major accomplishment in the effort to understand the effects of mechanical treatments in many forest types (Schwilk *et al.* 2009; Stephens *et al.* 2012; McIver *et al.* 2013). This study found that the most effective mechanical treatments varied markedly with forest type and often differed from prescribed fire treatments in both fuel reduction and ecosystem effects. Studies in ponderosa pine (*Pinus ponderosa*) forests showed that masticated treatments followed by prescription burning led to a greater reduction in both canopy and surface fuel load (Reiner *et al.* 2009; Kane *et al.* 2010; Knapp *et al.* 2011), yet had increased live shrub stem densities, compared with mastication alone (Kane *et al.* 2010; Potts *et al.* 2010). Differences in flame lengths and rate of spread of fire have been identified between different treatment types (Reiner *et al.* 2012; Kreye and Kobziar 2015) and modelled predictions of fire behaviour have been compared with actual fire behaviour in masticated treatments (Kobziar *et al.* 2009; Knapp *et al.* 2011). Laboratory studies have also been conducted to evaluate the effects of particle fracturing on moisture content and fire behaviour (Kreye *et al.* 2011, 2012), and the effects of fuel load and moisture content on fire behaviour and heating (Kreye *et al.* 2013). Particle fracturing did not affect fuel moisture drying times or fire behaviour, but fuel load and moisture content did influence fire behaviour and soil heating.

However, of particular concern, considering the cost of implementing these treatments (Vitorelo *et al.* 2009), is their long-term efficacy. The FFS study across a variety of ecosystems concluded that the effectiveness and longevity of treatments would depend in part on the response of herbs, tree seedlings and shrubs within each ecosystem (Schwilk *et al.* 2009; McIver *et al.* 2013). Recent studies in south-eastern pine flatwoods have reported rapid shrub recovery following mastication and have suggested a time-limited effectiveness and short-term efficacy in these systems (Kreye *et al.* 2014*b*; Kreye and Kobziar 2015), whereas studies from northern California chaparral identified individual species characteristics (i.e. resprouting *vs.* non-resprouting species) and the severity of treatments as determining factors of treatment efficacy (Potts and Stephens 2009; Kane *et al.* 2010; Potts *et al.* 2010). These results highlight the individuality of ecosystems and suggest that treatment efficacy will ultimately depend on individual site and stand characteristics.

To date, the bulk of information regarding masticated and other mechanically treated fuel beds comes from studies in coniferous forests, pine flatwoods and northern California chaparral. Relatively few studies have identified fuel bed characteristics and the effects of mastication or other mechanical treatments on southern California chaparral-dominated landscapes, despite the widespread use of these techniques across the region. The purpose of this study was to quantify changes in fuel structure following mechanical treatments and to assess treatment longevity in the chaparral-dominated systems of southern California. Our specific research questions were:

1. How do mechanical treatments alter the composition and structure of live and dead fuel components?
2. Are there differences in fuel composition and structure between treatment types?
3. Do pre-treatment stand age, vegetation type and time since treatment affect fuel load composition and structure?
4. How do mechanically treated fuels compare to untreated fuels?

Methods

Study area

Study sites were located within mechanical fuel treatments in the Angeles, Cleveland, Los Padres and San Bernardino national forests of southern California (Fig. 1). This area is encompassed by the South Coast Bioregion, which is characterised by a Mediterranean-type climate with hot, dry summers and cool, wet winters (Keeley 2006). The Los Padres, Angeles and northern portion of the San Bernardino national forests run from west to east within the Transverse Ranges, whereas the southern portion of the San Bernardino and the Cleveland national forests run from north to south in the Peninsular Ranges. These areas are geologically complex in age and composition with the western side of the Transverse Ranges being predominantly sedimentary and the eastern side of the Transverse Ranges and the Peninsular Ranges predominantly granitic (Norris and Webb 1990). The terrain is notably rugged with elevations from near sea level to 3506 m and slopes upwards of 50°.

A total of 62 separate fuel treatments in chaparral-dominated vegetation were utilised for this study including 42 mastication treatments, seven repeat-mastication treatments, nine mastication-plus-burning treatments and four crushing treatments (Fig. 2). All treatments were initially either masticated or crushed. Masticated treatments were completed using a 'masticator,' which consisted of a tracked-base machine and a cutting attachment that was either integrated into the machine or boom mounted. Base machines ranged from small Bobcat skid steers to large self-levelling Timco machines that incorporated a variety of different rotary head and horizontal drum cutting attachments. A total of 148 mastication study sites were established across all four forests with post-treatment ages that ranged from 1–8 years.

Crushing treatments, which are often used on steeper inclines, were less commonly employed due to accessibility issues and thus only 12 study sites were available. These treatments were implemented with a 'gravity roller,' which consisted of a 10-ton rolling steel cylinder connected to a bulldozer by two cables and two high-speed winches. The roller was lowered from the ridge top, crushing all vegetation in its path, and then winched back up to the dozer for the next run. All crushed sites were located in the Angeles National Forest with post-treatment ages of 2 and 4 years.

The remaining study sites were composed of secondary treatments to sites that were previously masticated. These were accomplished by either re-masticating or prescription burning the site. A total of 12 re-masticated and 19 masticated-plus-burned

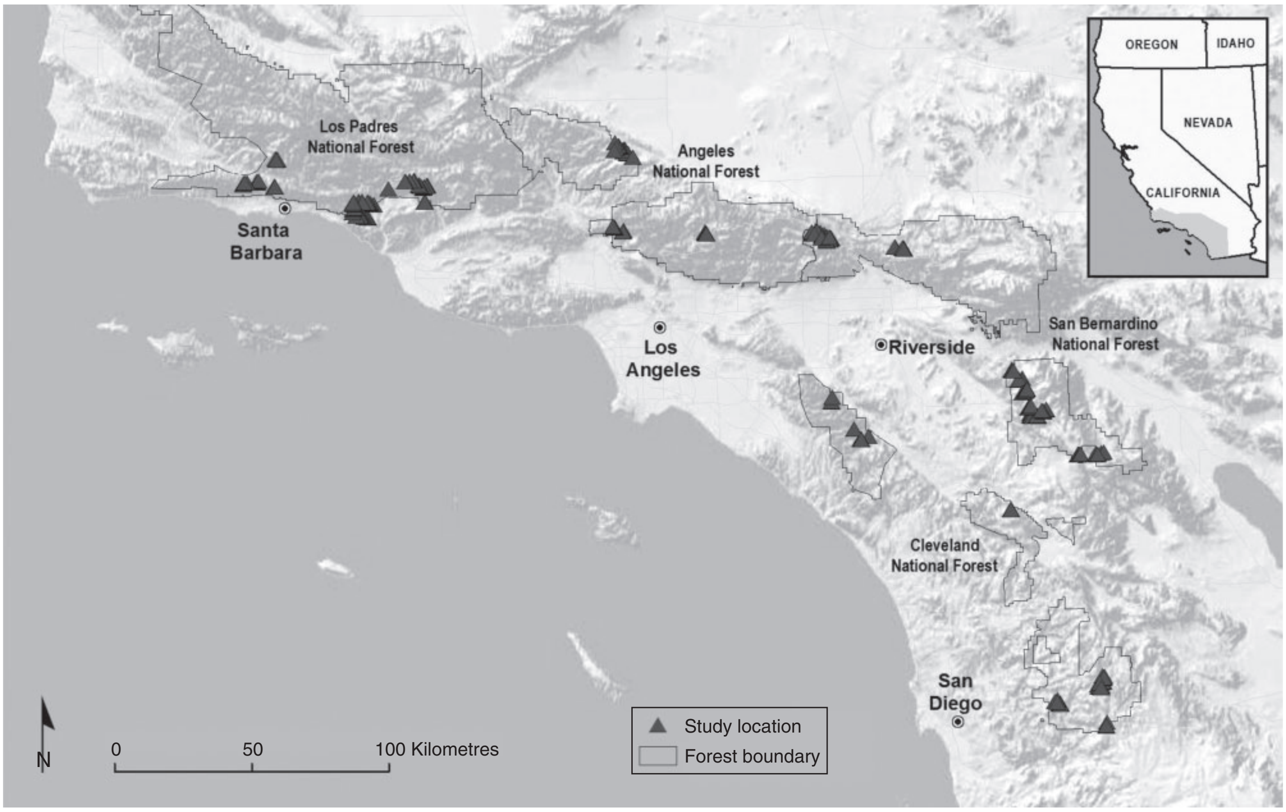

Fig. 1. Study site locations within mechanical treatments in the four southern California national forests.

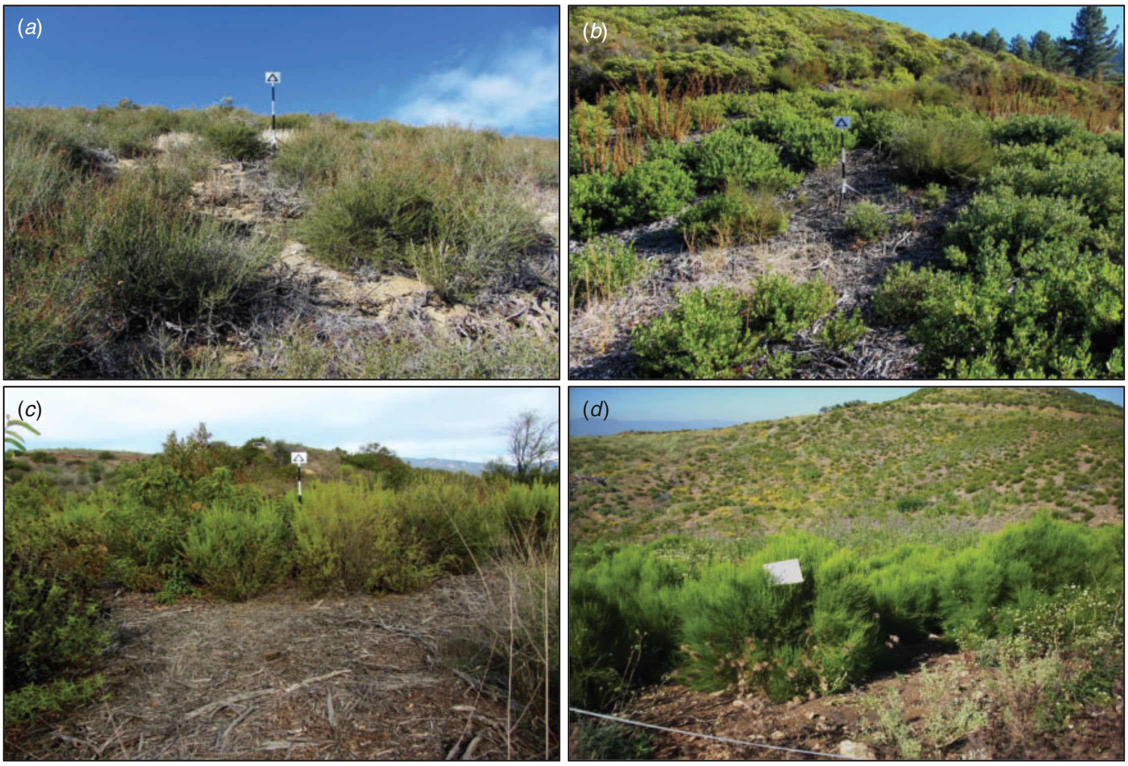

Fig. 2. Mechanical treatments by type: *a*) Two-year-old crushing treatment in *Adenostoma fasciculatum*; *b*) One-year-old mastication treatment in *Arctostaphylos glandulosa*; *c*) Three-year-old re-masticated treatment in a chaparral mix; *d*) One-year-old mastication-plus-burning treatment in *Adenostoma sparsifolium.*

sites were available in the Cleveland, Los Padres and San Bernardino national forests. The range of time between treatments for re-masticated sites was 2–5 years with a median of 4 years, whereas masticated-plus-burned treatments had a range of 1–5 years and a median time of 2 years between mastication and burning. The available time-since-treatment for re-masticated sites were 1, 3 and 4 years, whereas masticated-plus-burned sites had 1, 2 and 5 years between treatments.

The 191 study sites chosen for this study encompassed a wide range of chaparral communities and included stands dominated by individual species (>50% cover) of *Adenostoma fasciculatum*, *A. sparsifolium*, *Arctostaphylos* spp., *Ceanothus* spp. and *Quercus* spp. as well as mixed chaparral stands. The mean and median age of stands at the time of first treatment was 33 years, with a range of 7–64 years. The lowest elevation sites were located in the Los Padres National Forest near the coast with the highest elevation sites on the inland mountains of the San Bernardino National Forest. Inclines of treatments ranged from 2 to 50° and all slope aspects were represented within each treatment type.

Field and laboratory methods

Vegetation and fuel sampling was conducted in the summers of 2011 and 2012. Mechanical treatments were located using GIS data layers from the USGS Southern California Fuel Treatment Data Set and through field trips with fuels management personnel. All study sites were chosen using the ArcGIS random point generator and limited to areas at least 150 m within the treatment boundary at a spacing of 400 m between points. Controls were selected from untreated vegetation adjacent to the treatment area and represented the community before treatment.

Each study site consisted of a 10×100-m treatment plot placed perpendicular to the slope and subdivided into 10, 100-m^2 subplots, with a 1-m^2 quadrat nested in the upper left corner of each subplot. Intensive sampling of species composition and fuel structure was conducted in these treatment plots as described below. Less intensive sampling was done in the adjacent untreated vegetation with the goal of broadly characterising the characteristics of the vegetation before treatment. These control plots were 2×100 m and were placed adjacent to the treatment plots, 1 m inside the untreated vegetation to avoid edge effects. Site variables recorded were GPS location, elevation, aspect and incline.

Species composition in treatments was determined by recording cover and density of individual species within each of the 1-m^2 quadrats and listing additional species present in the rest of the 100-m^2 subplot. Cover was visually estimated and density was either counted or, when there were more than 30 individuals in the quadrat, estimated. Seedlings and resprouts were recorded separately. Species composition in controls was recorded in 1-m^2 quadrats placed every 10 m. Intensive fuel studies were not feasible for the controls, rather the objective was to collect height and cover values for each shrub species and use these data to estimate biomass from published fuel models. To do this we used a 2-m^2 quadrat placed every 10 m and recorded height and cover of the dominant shrubs present in the untreated vegetation. Stem samples from two obligate seeding individuals were collected from each control to determine pre-treatment stand age (Keeley 1993). Plant nomenclature followed Hickman (1993).

Fuel structure in treatments was determined using a destructive plot-based method similar to Kane *et al.* (2009), with three 0.5-m^2 plot frames placed along the outer edge of each of the five odd-numbered treatment subplots. Dead and downed fuels were collected at 3 m, herbaceous fuels and litter were collected at 7 m and live woody fuels were collected at the first intercept along the 10-m subplot. Average depth and height of each fuel class was recorded and all fuels contained within each plot frame were collected. Fuels intersecting the frame were cut so that only the material within the boundary was retained. Dead woody fuels were separated into 1-, 10-, 100- and 1000-h fuel classes with irregular-shaped particles being measured at the narrowest diameter (Kane *et al.* 2009). Herbaceous and litter fuels were separated into live and dead classes, with live woody fuels making up the final class. All collected fuels were weighed in the field to the nearest gram using hanging scales. A sample from each fuel class was bagged, weighed in the field, oven dried at the laboratory, and then reweighed to obtain fuel moisture. Final fuel masses were corrected for fuel moisture and expressed as oven dry weight. For treatments, cover was estimated for intact live woody fuel, herbaceous fuel, treatment debris and bare ground.

Analysis

Intensive study of fuels in the treatment plots was done by categorising fuels into one of four components: dead woody fuels comprising 1-, 10-, 100- and 1000-h fuel classes, dead herbaceous and litter fuels, live woody fuels and live herbaceous fuels. For comparison, crude estimates of fuel structure in adjacent control plots were made using the Fuel Characteristic Classification System (FCCS 2.2) (Prichard *et al.* 2013). Customised fuel loads in FCCS were obtained by choosing a model with the same cover type (i.e. chamise chaparral) and then inputting the height and percentage cover of each species present.

Fuel characteristics were summarised at the site level and descriptive statistics were calculated by treatment, vegetation type and time since treatment. Data by vegetation were grouped into burned and unburned treatments due to insufficient sample sizes within crushed and re-masticated treatments. Data assumptions of normality and equal variance were tested using Shapiro–Wilk and Levene tests, respectively, and when necessary, data were log or square root transformed to meet assumptions. Analysis of variance (ANOVA) was used to compare differences in fuel components between treatment types, vegetation types and time since treatment. Post hoc pairwise comparisons for significant ANOVA results ($P < 0.05$) were conducted using the Gabriel test to determine differences within fuel components by the specified factor. When the assumptions of ANOVA could not be met, a nonparametric Kruskal–Wallis test was employed. Post hoc comparisons for significant Kruskal–Wallis results ($P < 0.05$) were with Mann–Whitney tests. The Gabriel and Mann–Whitney tests were chosen because they both allow for comparisons between uneven sample sizes. Bivariate regression analyses were conducted using the ordinary least-squares model to determine if there were significant relationships ($P < 0.05$) between fuel components and independent site variables.

Treatments were compared with controls using the available live woody and live herbaceous fuel components. Paired *t*-tests were conducted to statistically determine significant differences between treated and untreated vegetation by treatment type, vegetation type and time since treatment. Differences between matched pairs were calculated and checked for normality using the Shapiro–Wilk test and were square root or log transformed when necessary. Proportions of the treatment to controls were calculated for each fuel component and ANOVA was used to compare the proportions to determine significant differences in treatment recovery by treatment type, vegetation type and time since treatment. Nonparametric data and post hoc tests for controls were managed in the same manner as for treatments. Bivariate regression analyses were conducted using the ordinary least-squares model to determine if there were significant relationships ($P < 0.05$) between the recovery of fuel components and time since treatment.

Results

Fuel structure and composition in treatments

Each of the four treatment types altered stand structure by converting live woody fuels to a compacted bed of downed woody fuels at the surface. Fuel bed components exhibited substantial site-to-site variability reflected in the ranges (Fig. 3) and standard deviations (Table 1). Total fuel load, which included live and dead components, was highest in crushed treatments with an average mass of 30.5 Mg ha^{-1}. The average

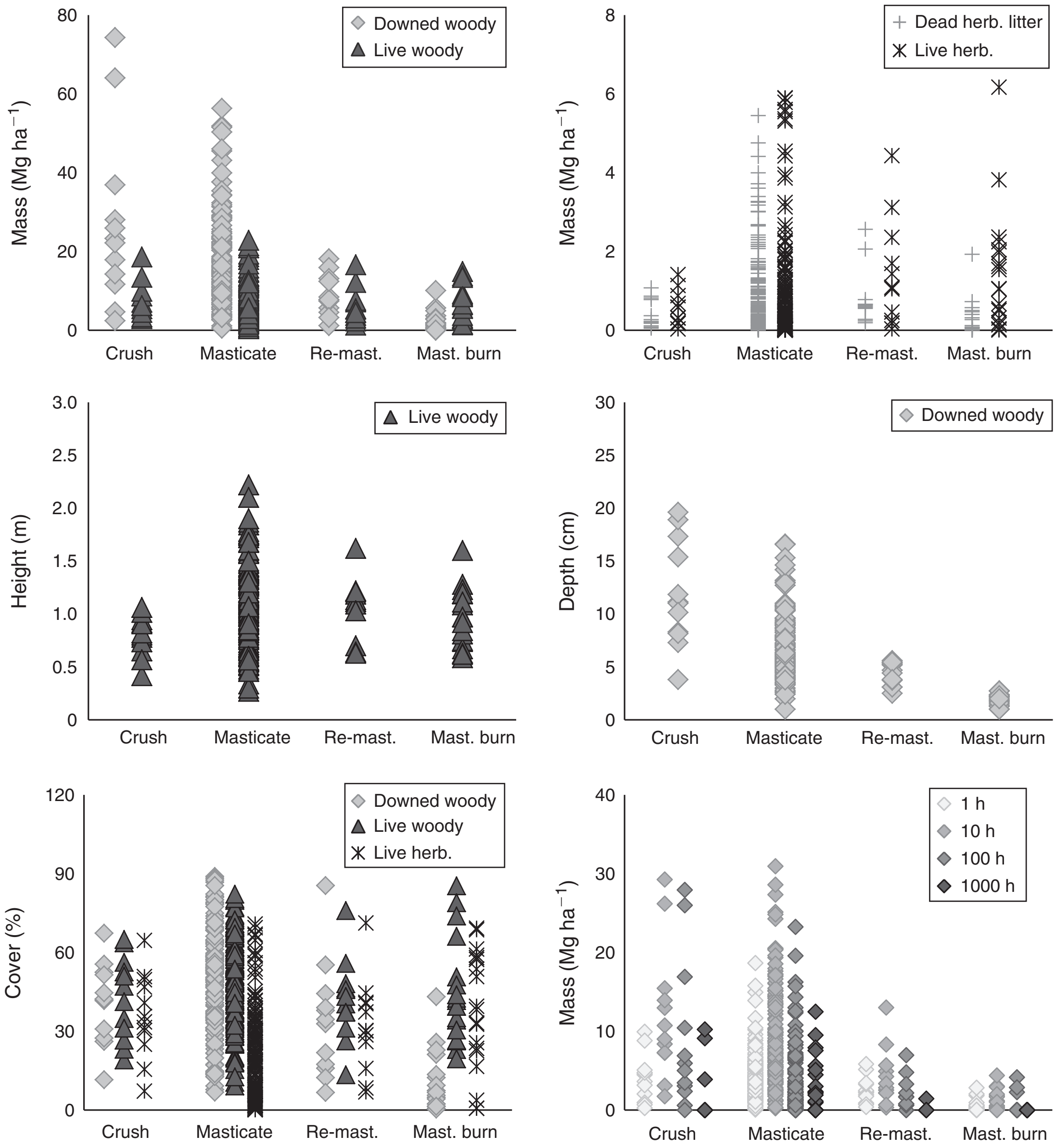

Fig. 3. Comparison of downed woody, live woody and herbaceous fuel components by treatment type.

total fuel load in masticated treatments was 26.2 Mg ha^{-1}, whereas second-entry treatments of re-mastication and mastication plus burning had significantly lower average total fuel load masses of 17.1 and 10.4 Mg ha^{-1}, respectively ($P < 0.001$). Live woody mass and cover were not statistically different between treatments and averaged 6.0 Mg $ha^{-1}$and 49%, respectively, across all treatment types (Fig. 3). Live woody height, in comparison, was significantly different between masticated and crushed treatments; the latter were three-quarters that of masticated treatments.

Herbaceous fuels were more variable and exhibited significant differences between treatment types for both the live and dead fractions (Table 1). Dead herbaceous and litter mass was on average 2–3 times higher in masticated and re-masticated treatments and was significantly different from treatments that were masticated plus burned (Fig. 3). Live herbaceous cover, alternatively, was highest in treatments that were masticated plus burned and lowest in single-entry mastication treatments with an average of 10–16% less cover than all other treatment types. Live herbaceous mass, on the other hand, was not significantly different between treatment types.

The largest differences between treatments were in the downed woody fuels. As a proportion of the total fuel load, these ranged widely across treatments and accounted for 76, 64, 55 and 19% of the total fuel load in crushed, masticated, re-masticated and masticated-plus-burned treatments, respectively. Significant differences were observed between treatment types in average cover, depth and mass (Table 1). Down-woody cover was highest in masticated and crushed treatments and on average covered ~45% of the ground surface (Fig. 3); however, this component in second-entry treatments had significantly less cover. Downed woody depth was statistically the deepest in crushed treatments and was approximately two times deeper than in masticated treatments, three times deeper than in re-masticated treatments and six times deeper than in masticated-plus-burned treatments. Downed woody depth was significantly correlated with downed woody mass ($r^2 = 0.62$, $P < 0.001$) and thus a similar trend was observed with crushed treatments having the highest average downed woody mass and masticated-plus-burned treatments the lowest.

A further analysis of downed woody mass by fuel size revealed significant differences between treatment types for all size classes except 1000-h fuels, which were relatively rare and never accounted for more than 7% by mass (Table 1). The lowest average masses of 1-, 10- and 100-h fuels were in masticated-plus-burned treatments, which were significantly different from all other treatments (Fig. 3). One-h fuel masses did not differ significantly across unburned treatment types, whereas re-masticated treatments had significantly lower masses of 10-h fuels in comparison with crushed treatments. One hundred-h fuels, conversely, had significantly higher masses in crushed treatments. All treatments, nevertheless, were proportionally dominated by the 10-h fuel size class, which accounted for 43–54% of the total downed woody fuel load (Fig. 4).

Effects of other variables on fuel components

Site and stand characteristics were assessed to evaluate potential effects on mechanical treatments; significant correlations were found between various fuel components and pre-treatment stand age, vegetation type and time since treatment. Bivariate regression analyses identified weak positive relationships in mastication treatments between pre-treatment stand age and both downed woody mass and cover ($r^2 = 0.08$ and 0.06, respectively, $P < 0.001$). In contrast, masticated-plus-burned treatments exhibited negative relationships between pre-treatment stand age and live woody mass ($r^2 = 0.27$, $P < 0.001$) and between pre-treatment stand age and dead herbaceous litter

Table 1. Summarised fuel bed characteristics by treatment type

ANOVA results for comparisons between treatment types with post hoc results indicated by superscripts. Values sharing superscripts (a and b) within rows are not significantly different ($P > 0.05$). Median (*Mdn*), mean and standard deviation presented *M*(*s.d.*)

		Crushed ($n = 12$)		Masticated ($n = 149$)		Re-masticated ($n = 14$)		Masticated & burned ($n = 19$)	
	ANOVA (*p*)	*Mdn*	*M*(*s.d.*)	*Mdn*	*M*(*s.d.*)	*Mdn*	*M*(*s.d.*)	*Mdn*	*M*(*s.d.*)
1-h mass (Mg ha^{-1})	<0.001	4.1	4.0(3.0) [a]	3.6	4.2(3.1) [a]	2.3	2.5(1.7) [a]	0.3	0.6(0.8)
10-h mass (Mg ha^{-1})	<0.001	9.9	12.1(8.4) [a]	6.7	8.5(6.3) [a]	3.1	4.2(3.5)	0.6	1.1(1.2)
100-h mass (Mg ha^{-1})	[A] <0.001	5.5	9.1(9.5)	1.8	3.3(4.1) [a]	1.2	1.9(2.1) [a]	0.0	0.5(1.2)
1000-h mass (Mg ha^{-1})	–	0.0	1.9(3.8) [a]	0.0	0.4(1.7) [a]	0.0	0.1(0.4) [a]	0.0	0.0(0.0) [a]
Downed woody mass (Mg ha^{-1})	<0.001	22.7	27.1(22) [a]	14.0	16.5(11.6) [ab]	7.7	8.8(5.1) [b]	1.6	2.2(2.6)
Downed woody depth (cm)	<0.001	11.1	11.9(4.9)	6.0	6.6(2.9)	4.6	4.4(1.1)	1.8	1.8(0.6)
Downed woody cover (%)	[A] <0.001	42.3	41.2(15.2) [ab]	50.0	48.3(19.9) [a]	33.8	33.7(21.8) [b]	5.6	9.9(11.2)
Live woody mass (Mg ha^{-1})	–	6.3	7.5(4.6) [a]	6.9	7.7(4.8) [a]	4.9	6.2(4.4) [a]	5.7	6.4(4.3) [a]
Live woody height (m)	0.038	0.8	0.8(0.2) [b]	1.1	1.1(0.4) [a]	1.1	1.0(0.3) [ab]	0.9	0.9(0.3) [ab]
Live woody cover (%)	–	44.2	42.7(15.7) [a]	50.7	49.4(16.6) [a]	41.9	42.4(16.9) [a]	39.5	43.8(19.3) [a]
Dead herbaceous litter mass (Mg ha^{-1})	[A] <0.001	0.2	0.4(0.4) [ab]	0.6	1.0(1.1) [a]	0.6	0.8(0.7) [a]	0.1	0.3(0.5) [b]
Live herbaceous mass (Mg ha^{-1})	–	0.4	0.5(0.4) [a]	0.5	1.0(1.4) [a]	1.1	1.4(1.4) [a]	1.1	1.5(1.5) [a]
Live herbaceous cover (%)	<0.001	34.7	36.0(15.9) [a]	19.0	21.8(16.9) [b]	30.2	31.7(17.5) [ab]	38.2	37.6(22.5) [a]

[A] Kruskal–Wallis test used due to failed assumptions of ANOVA.

mass ($r^2 = 0.25$, $P < 0.001$). No relationships between pre-treatment stand age and fuel structure were identified for either crushing or re-masticated treatments.

An ANOVA revealed several significant differences in fuel structure between vegetation types across unburned treatment types (Table 2). Average downed woody mass and cover were highest in treated *Arctostaphylos* spp. and *Quercus* spp. stands and lowest in *A. fasciculatum* and *Ceanothus* spp. stands. *Arctostaphylos* spp. stands, in particular, were significantly different from *Ceanothus* spp. stands and on average had twice the downed woody mass and 1.5 times the downed woody cover. Live woody fuels were not significantly different between vegetation types in average mass, yet significant differences were observed for both live woody height and cover. *Ceanothus* spp. and *Quercus* spp. treatments had the highest average heights and covers, *Arctostaphylos* spp. and *A. fasciculatum* treatments had the lowest average heights, and *A. sparsifolium* and mixed chaparral treatments had the lowest average covers.

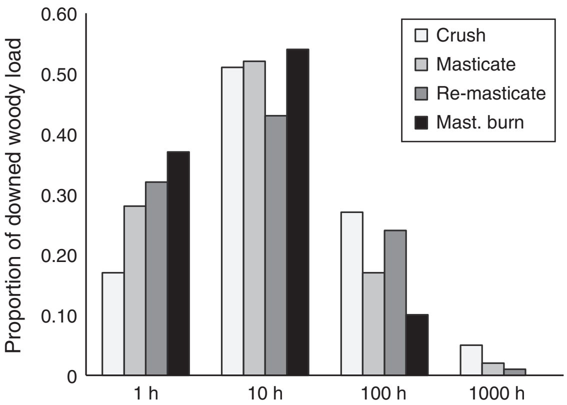

Fig. 4. Proportion of downed woody fuel load in 1-, 10-, 100- and 1000-h fuel size classes by treatment type.

Dead herbaceous litter fuels were also the highest in *Ceanothus* spp. and *Quercus* spp. treatments with masses that were significantly 2–3 times those observed in *A. sparsifolium* and *A. fasciculatum* treatments. Live herbaceous fuel mass, on the other hand, was highest in *A. fasciculatum* and *Ceanothus* spp. and lowest in *A. sparsifolium*. On average, treated stands of both *A. fasciculatum* and *Ceanothus* spp. had three times the live herbaceous fuel mass observed in *A. sparsifolium* treatments, which conversely had the highest live herbaceous cover. *A. sparsifolium* and mixed chaparral treatments had an average of 50% more live herbaceous cover than *Arctostaphylos* spp. treatments.

A comparison of fuel components by time since treatment, within individual treatment types, also identified several significant differences. All live and dead fuel components for masticated treatments, with the exception of live herbaceous mass, exhibited a significant difference between at least two separate time-since-treatment years (Table 3) (see Appendix 1, Tables A1 and A2 for post hoc results). Bivariate regression analyses further identified positive and negative relationships by time since treatment for live woody and downed woody fuel components, respectively (Fig. 5). These trends do not imply that fuel components within specific treatments increased or decreased over time, they simply show a relationship where time since treatment explains a percentage of the variation observed in the dependent variable. Herbaceous fuels, which exhibited significant differences in components between time-since-treatment years, did not reveal any relationships with time since treatment.

Analyses of the other treatments showed less variation in downed woody fuel components by times-since-treatment

Table 2. Post hoc comparison of crushed, re-masticated-plus-burned treatment

ANOVA results presented with mean and standard deviation (*s.d.*) for mass (Mg ha^{-1}), cover (%), height (m) and depth (cm) by fuel component. Values sharing superscripts (a, b, c, d) within rows are not significantly different ($P > 0.05$)

	ANOVA (p)	All unburned treatment types: *Adenostoma fasciculatum* $n = 31$	*Adenostoma sparsifolium* $n = 13$	*Arctostaphylos* spp. $n = 18$	*Ceanothus* spp. $n = 22$	*Chaparral mix* $n = 78$	*Quercus* spp. $n = 10$
1-h mass	–	3.7(2.1)^{a}	3.8(2.0)^{a}	5.3(3.6)^{a}	3.4(4.1)^{a}	4.4(3.1)^{a}	4.4(2.2)^{a}
10-h mass	<0.001	6.0(4.8)^{bc}	9.5(6.9)^{ac}	13.9(8.1)^{a}	4.7(4.4)^{b}	8.6(5.6)^{c}	10.4(6.9)^{abc}
100-h mass	–	2.3(5.0)^{a}	3.4(3.3)^{a}	4.1(4.3)^{a}	2.3(4.1)^{a}	3.5(3.5)^{a}	5.6(6.3)^{a}
1000-h mass	–	n/a	n/a	0.5(1.3)^{a}	n/a	0.7(2.3)^{a}	1.3(2.5)^{a}
Downed woody mass	0.046	12.0(10.8)^{ab}	16.7(8.3)^{ab}	23.8(14.7)^{b}	10.4(10.3)^{a}	17.2(10.4)^{b}	21.7(14.1)^{ab}
Downed woody depth	–	5.3(1.9)^{a}	7.4(2.7)^{a}	6.6(2.7)^{a}	6.0(3.4)^{a}	7.0(3.0)^{a}	7.8(3.0)^{a}
Downed woody cover	0.003	42.6(19.6)^{a}	52.2(16.1)^{ab}	62.2(18.1)^{b}	39.3(19.4)^{a}	47.1(19.3)^{a}	59.2(18.4)^{ab}
Live woody mass	–	7.0(3.6)^{a}	7.6(4.1)^{a}	9.2(5.3)^{a}	8.1(4.1)^{a}	7.1(5.2)^{a}	10.3(4.7)^{a}
Live woody height	0.001	1.0(0.3)^{a}	1.2(0.4)^{ab}	0.9(0.3)^{a}	1.3(0.4)^{b}	1.1(0.4)^{ab}	1.3(0.3)^{ab}
Live woody cover	0.020	50.4(17.0)^{ab}	43.4(10.7)^{ab}	51.1(19.6)^{ab}	59.5(16.1)^{a}	46.3(16)^{b}	54.2(14.7)^{ab}
Dead herbaceous litter mass	[A] <0.001	0.5(0.6)^{a}	0.6(0.6)^{a}	1.2(1.2)^{ab}	1.5(1.4)^{b}	1.0(1.0)^{ab}	1.6(1.1)^{b}
Live herbaceous mass	[A] <0.048	1.2(1.9)^{a}	0.4(0.4)^{b}	0.9(1.7)^{a}	1.2(1.5)^{a}	1.1(1.2)^{a}	0.7(0.8)^{ab}
Live herbaceous cover	0.009	19.2(15.3)^{ab}	26.8(20.4)^{ab}	13.5(16.4)^{a}	19.8(15.4)^{ab}	25.3(16.6)^{b}	16.3(15.2)^{ab}

[A]Kruskal–Wallis test used due to failed assumptions of ANOVA.

Table 3. Comparison of fuel components within treatment types by available time since treatment (years)

Results from ANOVA (p) and regression analyses (r^2) significant at <0.05. Direction of regression relationship is indicated by + or –. See Appendix 1, Tables A1 and A2 for post hoc results.

	Crushed (2 and 4)		Masticated (1–8)			Re-masticated (1, 3 and 4)			Masticated & burned (1, 2 and 5)		
	p	r^2	p	r^2		p	r^2		p	r^2	
1-h mass	–	n/a	<0.001	0.31	–	–	–		–	–	
10-h mass	–	n/a	<0.001	0.37	–	–	–		–	–	
100-h mass	–	n/a	<0.001	–		–	–		–	–	
1000-h mass	–	n/a	–	–		–	–		n/a	n/a	
Downed woody mass	–	n/a	<0.001	0.34	–	–	–		–	–	
Downed woody depth	–	n/a	<0.001	0.12	–	–	–		–	–	
Downed woody cover	0.007	n/a	<0.001	0.17	–	0.014	0.36	–	–	–	
Live woody mass	0.023	n/a	<0.001	0.15	+	–	–		<0.001	0.73	+
Live woody height	[A]0.037	n/a	<0.001	0.26	+	[A]0.007	0.44	–	[A]0.007	–	
Live woody cover	0.001	n/a	<0.001	0.26	+	–	–		[A]0.010	0.45	+
Dead herbaceous litter mass	–	n/a	[A]0.003	–		–	–		<0.001	–	
Live herbaceous mass	–	n/a	–	–		–	–		0.036	0.34	–
Live herbaceous cover	–	n/a	[A]0.016	–		–	–		–	0.22	–

[A]Kruskal–Wallis test used due to failed assumptions of ANOVA.

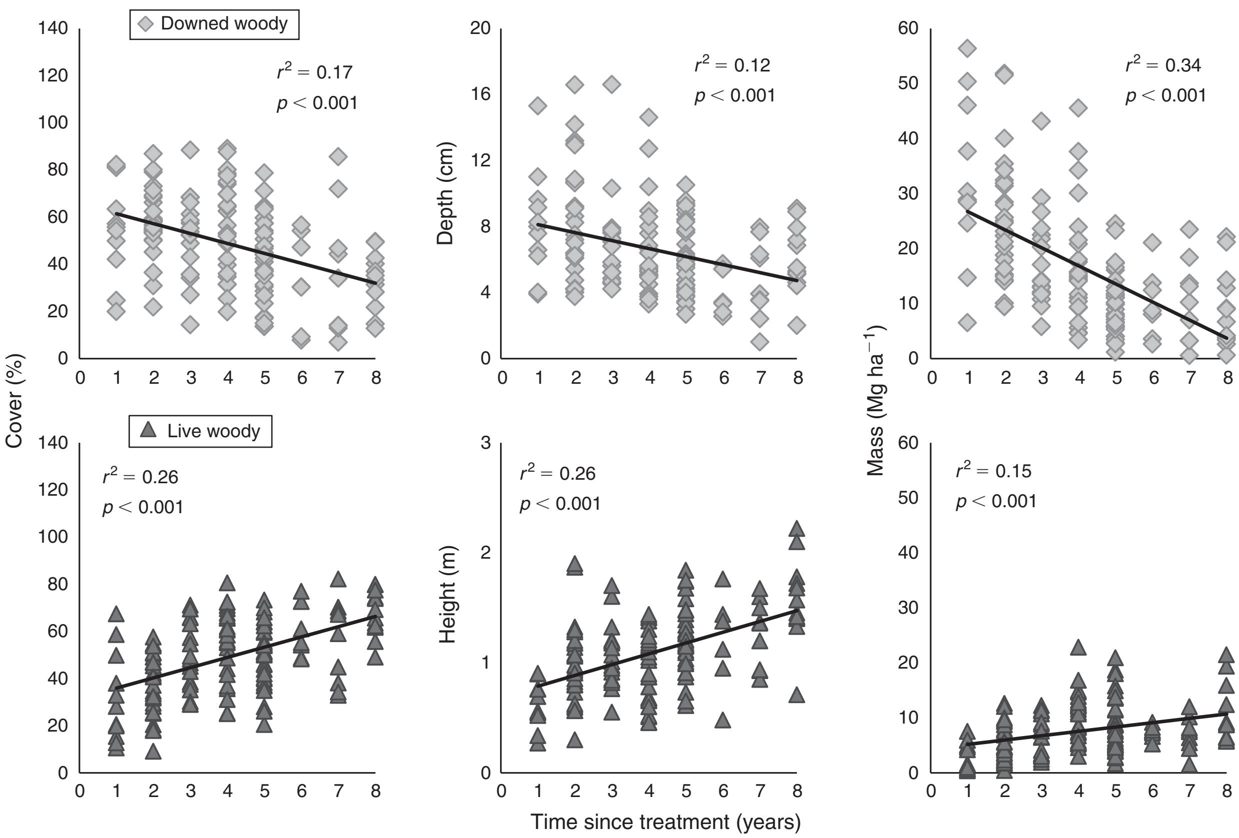

Fig. 5. Live woody and downed woody fuel components by time since treatment for masticated treatments.

(Table 3). Crushed treatments led to significant differences within live woody fuel components but not within herbaceous fuel components, whereas re-masticated treatments exhibited less variation across all fuel components. Masticated-plus-burned treatments, in contrast, exhibited significant differences by time since treatment within all live woody fuel components, as well as both live and dead herbaceous mass. Live woody mass and cover were positively correlated with

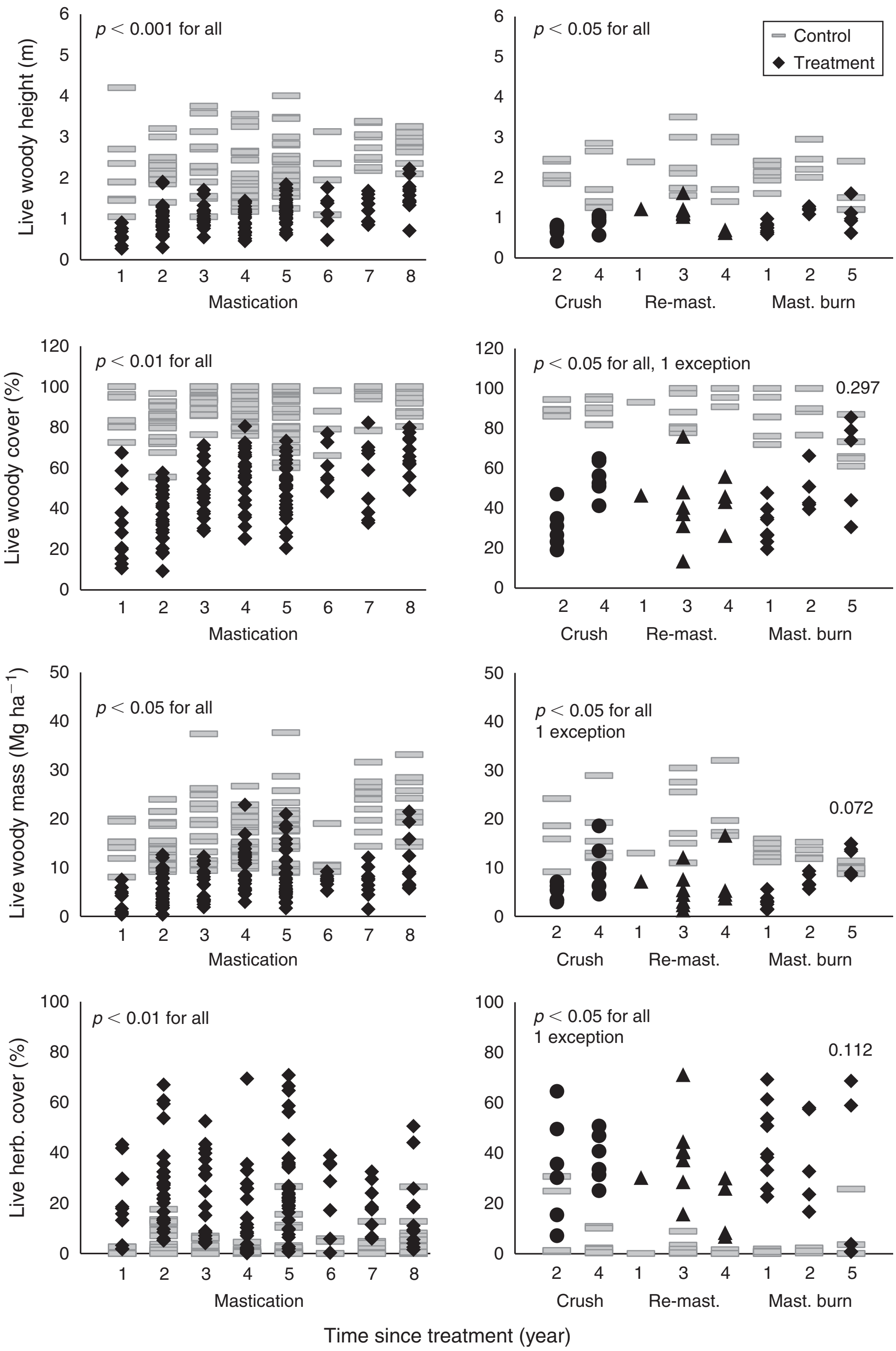

Fig. 6. Live woody and herbaceous fuel components in treatments and controls by treatment type and time since treatment. Paired *t*-test results for each time-since-treatment year presented.

time since treatment, whereas live herbaceous mass and cover were negatively correlated.

Comparison with untreated vegetation

Paired *t*-tests of treatments and controls showed that treatments were significantly different from controls for all live woody and herbaceous fuel components by treatment type ($P < 0.001$) and vegetation type ($P < 0.05$). Treatments were also significantly different from controls by time since treatment for all treatment types except mastication plus burning (Fig. 6.) Time-since-treatment years 1 and 2, in masticated-plus-burned treatments, were significantly different from controls, whereas year 5 showed no statistical differences in live woody mass, live woody

Table 4. Comparison of proportion of treatment to control by treatment type and vegetation type

ANOVA results presented (p) with mean and (standard deviation). Post hoc results indicated by superscripts. Values sharing the same letter (a, b) within columns are not significantly different ($P > 0.05$)

	Live woody cover (%)	Live woody height (m)	Live woody mass (Mg ha^{-1})	Live herbaceous cover (%)
Treatment type (p)	–	–	–	0.027
Crushed	0.48(0.17)	0.50(0.16)	0.49(0.30)	12.0(11.4)^{a}
Masticated	0.56(0.18)	0.42(0.15)	0.45(0.24)	11.8(9.5)^{ab}
Re-masticated	0.47(0.20)	0.49(0.21)	0.39(0.36)	20.4(19.0)^{b}
Masticated & burned	0.55(0.28)	0.48(0.17)	0.56(0.44)	19.6(14.5)^{b}
Vegetation type (p)	–	–	–	–
Adenostoma fasciculatum	0.61(0.25)	0.53(0.17)	0.52(0.33)	12.9(11.9)
Adenostoma sparsifolium	0.51(0.12)	0.52(0.19)	0.58(0.32)	11.8(9.9)
Arctostaphylos spp.	0.56(0.21)	0.48(0.13)	0.58(0.31)	11.5(10.3)
Ceanothus spp.	0.61(0.17)	0.48(0.18)	0.35(0.27)	12.4(15.2)
Chaparral mix	0.51(0.19)	0.48(0.16)	0.46(0.30)	14.7(13.1)
Quercus spp.	0.55(0.15)	0.44(0.17)	0.61(0.38)	9.2(11.1)

Table 5. Comparison of proportion of treatment to control by treatment type and available time since treatment (years)

Results from ANOVA (p) and regression analyses (r^2) significant at <0.05. Direction of regression relationship is indicated by + or –. Note: See Appendix 1, Table A3 for post hoc results

	Crushed (2 and 4)		Masticated (1–8)			Re-masticated (1, 3 and 4)		Masticated & burned (1, 2 and 5)		
	p	r^2	p	r^2		p	r^2	p	r^2	
Live woody cover	0.001	n/a	<0.001	0.26	+	–	–	[A]0.012	0.58	+
Live woody height	0.045	n/a	0.001	0.09	+	–	–	<0.001	0.74	+
Live woody mass	0.006	n/a	0.003	–		–	–	<0.001	0.88	+
Live herbaceous cover	–	n/a	–	–		–	–	0.002	0.48	–

[A]Kruskal–Wallis test used due to failed assumptions of ANOVA.

cover or live herbaceous cover. Live woody height, however, was still significantly different from controls at year 5.

Calculations of the proportion of live woody fuel in treatments compared with controls found no statistical differences in the recovery of cover, height and mass by treatment type or vegetation type (Table 4). Average live woody cover and height, in general across all treatment types, was around half of the average cover and height observed in controls. Average live woody mass was also around half of the FCCS calculated live woody mass for controls. The proportion of live herbaceous cover in treatments compared with controls, conversely, was significantly different by treatment type (Table 4). Masticated and crushed treatments, on average, had 12 times the live herbaceous cover observed in controls, whereas re-masticated and masticated-plus-burned treatments had 20 times the live herbaceous cover observed in controls. No differences, however, were found by vegetation type.

Neither vegetation type nor treatment type alone affected live woody recovery in treatments. On the other hand, more detailed analysis by treatment type, as well as time since treatment, did identify differences between the proportions of live woody fuel characteristics in treatments compared with controls, for all treatment types except re-mastication (Table 5) (see Appendix 1, Table A3 for post hoc results). Proportions of live woody cover and live woody height for masticated and masticated-plus-burned treatments exhibited positive relationships with time since treatment. These relationships, however, were much stronger for masticated-plus-burned treatments, which also exhibited a significantly strong positive relationship with live woody mass. Proportions of live herbaceous cover, alternatively, were only significantly different between time-since-treatment years in masticated-plus-burned treatments, where they exhibited a significant negative relationship with time since treatment.

Discussion

In this southern California chaparral study, all fuel treatment types significantly altered fuel structure and composition in comparison with untreated vegetation. The resultant fuel structures and composition, however, varied by treatment type with significant differences in downed woody fuel components and live herbaceous cover. A comparison of downed woody fuel characteristics in our study to those in previous studies in masticated chaparral showed similar average fuel depths with seemingly different average fuel loads. A study in northern California reported a range of downed woody fuel loads from 23–64 Mg ha^{-1} with depths of 3–8 cm (Kane *et al.* 2009), and a study in southern California, reported average fuel load and depth of 29 Mg ha^{-1} and 3 cm (Reiner and Decker 2009). Single-entry mastication treatments in our study had an average downed woody fuel depth of 6 cm with a substantially lower average fuel load of 17 Mg ha^{-1}. Re-masticated treatments averaged 5 cm in depth with a fuel load of 9 Mg ha^{-1}, whereas crushed treatments, had a deeper average downed woody fuel depth of 12 cm, with a more similar average fuel load of 27 Mg ha^{-1}.

Mastication field data for both of the abovementioned studies were collected within the first 3 years following treatment (Kane *et al.* 2009; Reiner and Decker 2009), whereas our mastication data spanned a post-treatment period of 8 years. Data from our crushing treatments were from 2-and 4-year-old treatments and thus were more comparable. A calculation of average downed woody fuel load using a subset of our data from 1–3-year-old treatments, on the other hand, more closely resembled the findings from these other studies with an average mass of 24 Mg ha^{-1}. Masticated-plus-burned treatments had the lowest average downed woody fuel depths (1–3 cm) with average fuel loads in the range 1–10 Mg ha^{-1}. These results were similar to observations from a study in masticated-plus-burned ponderosa pine with a shrub-dominated midstorey, which reported an average fuel depth of 4 cm and an average mass at just under 10 Mg ha^{-1} (Kane *et al.* 2010; Knapp *et al.* 2011).

To date, most studies have focussed primarily on changes in fuel structure based on various woody-fuel components. The increase of herbaceous fuels, however, also plays a role in changing the structure and composition of fuels at the surface. Herbaceous fuels are finer and more flammable, and they increase surface fuel depths as well as fuel continuity. Results from our study show significant increases in herbaceous fuels following all treatment types, which was also observed in northern California chaparral (Kane *et al.* 2009; Potts and Stephens 2009) and in ponderosa pine with a shrub-dominated midstorey (Kane *et al.* 2010). Mastication treatments in mixed-conifer and forest-dominated systems, in contrast, tended to have increased, but lower herbaceous fuel loads following treatment than shrub-dominated sites (Kane *et al.* 2009; Reiner and Decker 2009; Wolk and Rocca 2009; Battaglia *et al.* 2010).

Treatment longevity

Treatment longevity is a concern with any fuel treatment. More recently, however, it has become a pressing issue as the cost to prevent, mitigate and suppress wildfires continues to increase (NIFC, 2013). A complication in determining treatment longevity is that it is subjective and dependent on individual vegetation management objectives. For instance, the goal for one forest was to maintain chaparral in a seral stage across large areal treatments, and the goal for another was to permanently type-convert treatment areas along ridgeline fuelbreaks. The specific objectives of each treatment varied; some specified a percentage of cover to be retained or species to be avoided, whereas others focussed on complete alteration of all fuels. Each of these factors affects the resultant fuel structure and perceived longevity of a given treatment.

Despite these differing management objectives, our results showed that recovering live woody fuel was the most important factor determining treatment longevity. Chaparral ecosystems, which are prone to periodic wildfires, have a large number of species that are able to resprout from basal underground structures when damaged (Keeley 2001). These obligate resprouting species require no establishment period and do not appear to be hindered by downed woody debris cover (Kane *et al.* 2010). These results are similar to those of several other studies that have also concluded that the primary limiting factor of long-term effectiveness in mechanical treatments is the rapid recovery of live woody fuels (Schwilk *et al.* 2009; Kane *et al.* 2010; Potts *et al.* 2010; Kreye *et al.* 2014*b*; Kreye and Kobziar 2015).

Our analysis by time since treatment also revealed some interesting differences in shrub recovery between treatment types. Masticated-plus-burned treatments had the strongest relationship between live woody recovery variables and time since treatment and were similar to controls at post-treatment year 5. Live woody recovery variables in single-entry mastication treatments, on the other hand, had weaker, positive relationships with time since treatment and when compared with masticated-plus-burned treatments at post-treatment year 5 showed 30% less recovery in plant cover and 14% less recovery in height. This implies that masticated-plus-burned treatments will have a shorter effectiveness period than single-entry mastication treatments. Crushed treatments were similar in recovery to single-entry mastication treatments at post-treatment year 4, indicating similar longevity, whereas re-masticated treatments had 18% less recovery of both live woody cover and height. These results suggest that masticated-plus-burned treatments will have the shortest longevity, whereas re-masticated treatments will have the longest. It should also be noted that re-masticated treatments had the highest proportion of herbaceous cover in comparison to controls with no relationship between live woody recovery and time since treatment. These results indicate that re-masticated treatments are showing signs of type conversion, which may or may not be a desired result depending on management objectives.

Management implications

Although it is clear that mastication and crushing treatments reduce canopy height and create densely compacted fuel beds, it should not be overlooked that there are drawbacks and concerns to using these treatments widely across landscapes. One of the primary alterations to fire behaviour in masticated fuel beds is long-duration combustion. When densely compacted fuel beds are subjected to longer duration combustion, heat energy can be re-directed to the underlying soil, potentially damaging underground plant structures (Busse *et al.* 2005; Kreye *et al.* 2012), and depleting native plant seed banks (Kane *et al.* 2009). This in turn can lead to non-native plant establishment and vegetative community changes (Keeley *et al.* 2008; Kane *et al.* 2009; Keeley and Brennan 2012). Residual flaming and smouldering can also complicate fire behaviour, leading to fire control issues (Knapp *et al.* 2011; Kreye *et al.* 2014*a*) and emission problems due to increased smouldering consumption (Reinhardt *et al.* 1997; Ottmar 2014).

In addition, alterations in fuel structure from a 2–3-m high homogenous live canopy to a compacted layer of dead fuels less than 10 cm increases solar radiation input and surface winds, which in turn decrease fuel moisture (Agee and Skinner 2005). Recent studies have identified reduced fuel moisture in masticated treatments as a primary driver of increased flame length, rate of spread and fireline intensity (Knapp *et al.* 2011; Kreye *et al.* 2011; Brewer *et al.* 2013; Kreye *et al.* 2013). Climatic variables specific to southern California, including hot summers, prolonged drought periods and Santa Ana wind events, exacerbate decreased fuel moistures, which may intensify fire behaviour in these treatments.

A further complication of the widespread use of mechanical treatments is the increase in both native and non-native herbaceous fuels. Non-native species, and in particular non-native annual grasses, are highly flammable species that tend to cure earlier in the season than native plants and thereby shorten the length of time during which fuel moisture may inhibit fire ignition potential (Keeley 2001; Brooks *et al.* 2004). Careful consideration should go into using these treatments at the wildland–urban interface where sources for ignition are the greatest (Syphard and Keeley 2015). Further details and discussion are available in the Supplementary material, available online.

Conclusions

Increased use of mechanical treatments in chaparral, especially at the wildland–urban interface, warrants the need for more intensive research to better understand fire behaviour in these altered- fuels landscapes. Consequences of not understanding the effects of treatments over time are potentially serious, posing a risk to human safety as well as natural resources. Empirical data from studies evaluating the effects of mastication on actual fire behaviour are needed to create and validate masticated fuel models that can accurately predict fire behaviour in these complicated fuel structures. Managers in turn would then be able to integrate this information into fuels management decisions.

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References

Agee JK, Skinner C (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034

Battaglia MA, Rocca ME, Rhoades CC, Ryan MG (2010) Surface fuel loadings within mulching treatments in Colorado coniferous forests. *Forest Ecology and Management* **260**, 1557–1566. doi:10.1016/J.FORECO.2010.08.004

Brewer NW, Smith AMS, Higuera PE, Hatten JA, Hudak AT, Ottmar RD, Tinkman WT (2013) Fuel moisture influences on fire-altered carbon in masticated fuels: an experimental study. *Journal of Geophysical Research* **118**, 30–40.

Brooks ML, D'Antonio CM, Richardson DM, Grace JB, Keeley JE, DiTomaso JM, Hobbs RJ, Pellant M, Pyke D (2004) Effects of invasive alien plants on fireregimes. *Bioscience* **54**, 677–688. doi:10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2

Busse MD, Hubbert KR, Fiddler GO, Shestak CJ, Powers RF (2005) Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* **14**, 267–276. doi:10.1071/WF04062

Glitzenstein JL, Streng DR, Achtmeier GL, Naeher LP, Wade DD (2006) Fuels and fire behavior in chipped and unchipped plots: implications for land management near the wildland/urban interface. *Forest Ecology and Management* **236**, 18–29. doi:10.1016/J.FORECO.2006.06.002

Hickman JC (Eds) (1993) 'The Jepson Manual: Higher Plants of California.' (University of California Press: Berkeley)

Hood S, Wu R (2006) Estimating fuel bed loadings in masticated areas. In 'Fuels Management – How to Measure Success', 27–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 333–340. (Fort Collins, CO)

Hudak AT, Rickert I, Morgan P, Strand E, Lewis SA, Robichaud PR, Hoffman C, Holden ZA (2011) Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central, Idaho, USA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-252. (Fort Collins CO)

Kane JM, Knapp EE, Varner JM (2006) Variability in loading of mechanically masticated fuel beds in northern California and southwestern Oregon. In 'Fuels Management – How to Measure Success', 27–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 341–350. (Fort Collins, CO)

Kane JM, Varner JM, Knapp EE (2009) Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. *International Journal of Wildland Fire* **18**, 686–697. doi:10.1071/WF08072

Kane JM, Varner JM, Knapp EE, Powers RF (2010) Understory vegetation response to mechanical mastication and other fuels treatments in a ponderosa pine forest. *Applied Vegetation Science* **13**, 207–220. doi:10.1111/J.1654-109X.2009.01062.X

Keeley JE (1993) Utility of growth rings in the age determination of chaparral shrubs. *Madrono* **40**, 1–14.

Keeley JE (2001) Fire and invasive species in Mediterranean-climate ecosystems of California. In 'Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species'. Available at http://www.globalrestorationnetwork.org/uploads/files/LiteratureAttachments/144_fire-and-invasive-species-in-mediterranean-climate-ecosystems-of-california.pdf [Verified 6 July 2015])

Keeley JE (2006) South coast bioregion. In 'Fire in California's Ecosystems.' (Eds NG Sugihari, JW van Wagtendonk, KE Shaffer, J Fites-Kaufman, AE Thode,) pp. 350–390. (University of California Press: Berkeley)

Keeley JE, Brennan TJ (2012) Fire-driven alien invasion in a fire-adapted ecosystem. *Oecologia* **169**, 1043–1052. doi:10.1007/S00442-012-2253-8

Keeley JE, Brennan TJ, Pfaff AH (2008) Fire severity and ecosystem responses following crown fires in California shrublands. *Ecological Applications* **18**(6), 1530–1546. doi:10.1890/07-0836.1

Knapp EE, Varner JM, Busse MD, Skinner CN, Shestak CA (2011) Behaviour and effects of prescribed fire in masticated fuelbeds. *International Journal of Wildland Fire* **20**, 932–945. doi:10.1071/WF10110

Kobziar LN, McBride JR, Stephens SL (2009) The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. *International Journal of Wildland Fire* **18**, 791–801. doi:10.1071/WF06097

Kreye JK, Kobziar LN (2015) The effect of mastication on surface fire behaviour, fuels consumption and tree mortality in pine flatwoods of Florida, USA. International Journal of Wildland Fire 24, 573–579. doi:10.1071/WF14186

Kreye JK, Varner JM, Knapp EE (2011) Effects of particle fracturing and moisture content on fire behavior in masticated fuel beds burned in a laboratory. *International Journal of Wildland Fire* **20**, 308–317. doi:10.1071/WF09126

Kreye JK, Varner JM, Knapp EE (2012) Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuel bed compaction. *International Journal of Wildland Fire* **21**, 894–904. doi:10.1071/WF11077

Kreye JK, Kobziar LN, Zipperer WC (2013) Effects of fuel load and moisture content on fire behavior and heating in masticated litter-dominated fuels. *International Journal of Wildland Fire* **22**, 440–445. doi:10.1071/WF12147

Kreye JK, Brewer NW, Morgan P, Varner JM, Smith AMS, Hoffman CM, Ottmar RD (2014*a*) Fire behavior in masticated fuels: a review. *Forest Ecology and Management* **314**, 193–207. doi:10.1016/J.FORECO.2013.11.035

Kreye JK, Kobziar LN, Camp JM (2014*b*) Immediate and short-term response of understory fuels following mechanical mastication in a pine flatwoods site of Florida, USA. *Forest Ecology and Management* **313**, 340–354. doi:10.1016/J.FORECO.2013.10.034

McIver JD, Stephens SL, Agee JK, Barbour J, Boerner REJ, Edminster CB, Erickson KL, Farris KL, Fettig CJ, Fielder CE, Haase S, Hart SC, Keeley JE, Knapp EE, Lehmkuhl JF, Moghaddas JJ, Otrosina W, Outcalt KW, Schwilk DW, Skinner CN, Waldrop TA, Weatherspoon CP, Yaussy DA, Youngblood A, Zack S (2013) Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). *International Journal of Wildland Fire* **22**, 63–82. doi:10.1071/WF11130

Miller C (2007) Wildfire underwriting in California: an industry perspective. In 'Living on the Edge: Advances in the Economics of Environmental Resources, Vol. 6'. (Eds A Troy, RG Kennedy) pp. 121–125. (Emerald Group Publishing: Bingley, UK)

National Interagency Fire Center (NIFC) (2013) Wildland fire summary and statistics annual report 2013. Available at http://www.predictiveservices.nifc.gov/intelligence/intelligence.htm [Verified 29 June 2015]

Norris RM, Webb RW (1990) 'Geology of California.' 2nd edn. (John Wiley & Sons Inc.:New York, NJ)

Ottmar RD (2014) Wildland fire emissions, carbon, and climate: modeling fuel consumption. *Forest Ecology and Management* **317**, 41–50. doi:10.1016/J.FORECO.2013.06.010

Potts JB, Stephens SL (2009) Invasive and native plant responses to shrubland fuel reduction: comparing prescribed fire, mastication, and treatment season. *Biological Conservation* **142**, 1657–1664. doi:10.1016/J.BIOCON.2009.03.001

Potts JB, Marino E, Stephens SL (2010) Chaparral shrub recovery after fuel reduction: a comparison of prescribed fire and mastication techniques. *Plant Ecology* **210**, 303–315. doi:10.1007/S11258-010-9758-1

Prichard SJ, Sandberg DV, Ottmar RD, Eberhardt E, Andreu A, Eagle P, Swedin K (2013) Fuel Characteristic Classification System version 3.0: technical documentation. USDA Forest Service, Pacific Northwest Research Station, General Technical Report. PNW-GTR-887. (Portland, OR)

Reiner AL, Decker ST (2009) Fuel loadings in masticated areas on the San Jacinto District of the San Bernardino National Forest. USDA Forest Service, Adaptive Management Services Enterprise Team. (Sparks, NV)

Reiner AL, Vaillant NM, Fites-Kaufman J, Dailey SN (2009) Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada. *Forest Ecology and Management* **258**, 2365–2372. doi:10.1016/J.FORECO.2009.07.050

Reiner AL, Vaillant NM, Dailey SN (2012) Mastication and prescribed fire influences on tree mortality and predicted fire behavior in ponderosa pine. *Western Journal of Applied Forestry* **27**(1), 36–41.

Reinhardt ED, Keane RE, Brown JK (1997) First Order Fire Effects Model: FOFEM 4.0 user's guide. USDA Forest Service, Intermountain Research Station, General Technical Report. INT-GTR-344. (Ogden UT)

Schwilk DW, Keeley JE, Knapp EE, McIver J, Bailey JD, Fettig CJ, Fiedler CE, Harrod RJ, Moghaddas JJ, Outcalt KW, Skinner CN, Stephens SL, Waldrop TA, Yaussy DA, Youngblood A (2009) The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. *Ecological Applications* **19**(2), 285–304. doi:10.1890/07-1747.1

Stephens SL, Moghaddas JJ (2005) Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management* **215**, 21–36. doi:10.1016/J.FORECO.2005.03.070

Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR, Kennedy PL, Schwilk DW (2012) The effects of forest fuel-reduction treatments in the United States. *Bioscience* **62**, 549–560. doi:10.1525/BIO.2012.62.6.6

Syphard AD, Keeley JE (2015) Location, timing, and extent of wildfire vary by cause of ignition. *International Journal of Wildland Fire* **24**(1), 37–47. doi:10.1071/WF14024

Syphard AD, Keeley JE, Brennan TJ (2011) Comparing the role of fuel breaks across southern California national forests. *Forest Ecology and Management* **261**, 2038–2048. doi:10.1016/J.FORECO.2011.02.030

Vitorelo B, Han HS, Varner JM (2009) Masticators for fuel reduction treatment: equipment options, effectiveness, costs, and environmental impacts. In 'Proceedings of the 2006 Council on Forest Engineering (COFE) meeting', p. 11. (Lake Tahoe, CA) Available at http://web1.cnre.vt.edu/forestry/cofe/documents/COFE_2009_Vitorelo_et_al.pdf [Verified 29 June 2015]

Wolk B, Rocca ME (2009) Thinning and chipping small-diameter ponderosa pine changes understory plant communities on the Colorado Front Range. *Forest Ecology and Management* **257**(1), 85–95. doi:10.1016/J.FORECO.2008.08.014

Appendix 1. Post hoc results from ANOVA analyses

Table A1. Post hoc comparison of masticated treatments by time since treatment (TST)

ANOVA results presented with mean and standard deviation (s.d.) for mass (Mg ha^{-1}), cover (%), height (m) and depth (cm) by fuel component. Values sharing superscripts (a, b, c, d) within rows are not significantly different ($P > 0.05$)

		Masticated							
TST (year)		1	2	3	4	5	6	7	8
ANOVA (*p*)		(*n* = 12)	(*n* = 29)	(*n* = 18)	(*n* = 26)	(*n* = 36)	(*n* = 7)	(*n* = 9)	(*n* = 12)
1-h mass	<0.001	7.4(4.0)^{a}	5.2(2.0)^{a}	6.5(4.3)^{a}	4.3(2.5)^{ab}	2.5(1.3)^{c}	2.7(2.5)^{bc}	2.0(1.6)^{c}	2.5(2.1)^{bc}
10-h mass	<0.001	16.4(8.6)^{a}	13.3(5.7)^{a}	8.9(4.2)^{ab}	8.7(6.1)^{bc}	5.1(3.0)^{cd}	5.4(4.6)^{bcd}	5.3(3.7)^{bcd}	3.1(2.4)^{d}
100-h mass	<0.001	7.3(4.4)^{a}	5.5(5.8)^{ab}	2.3(2.8)^{bc}	2.8(2.7)^{abc}	2.0(2.6)^{c}	0.8(1.1)^{c}	2.7(4.2)^{abc}	3.5(4.5)^{abc}
1000-h mass	–	3.1(8.2)^{a}	0.8(2.7)^{a}	0.1(0.2)^{a}	0.7(2.1)^{a}	0.2(0.9)^{a}	1.1(2.9)^{a}	0.3(0.8)^{a}	0.0(0.0)^{a}
Total downed woody mass	<0.001	34.1(15.9)^{a}	24.7(11.2)^{ab}	17.8(9.0)^{bc}	16.5(10.5)^{cd}	9.7(5.5)^{d}	10(6.4)^{cd}	10.3(7.6)^{cd}	9.1(7.1)^{cd}
Downed woody depth	<0.001	8.1(3.1)^{a}	8.1(3.5)^{a}	6.9(2.9)^{ab}	6.5(2.7)^{ab}	6.1(2.2)^{ab}	4.1(1.4)^{b}	4.7(2.4)^{b}	6.0(2.1)^{ab}
Downed woody cover	<0.001	55.3(20.3)^{abc}	58.6(14.0)^{a}	51.1(17.5)^{abcd}	56.4(19.8)^{ab}	41.5(16.8)^{cd}	33.6(20.1)^{bcd}	36.6(28.0)^{bcd}	33(12.1)^{d}
Live woody mass	<0.001	3.6(2.6)^{a}	5.4(3.3)^{a}	6.7(3.4)^{ab}	10.1(4.5)^{b}	8.5(4.9)^{b}	7.4(1.2)^{ab}	7.0(3.1)^{ab}	11.6(7.5)^{b}
Live woody height	<0.001	0.7(0.3)^{a}	1.0(0.4)^{ab}	1.0(0.3)^{b}	1.0(0.3)^{ab}	1.2(0.3)^{b}	1.2(0.4)^{bc}	1.3(0.3)^{bc}	1.6(0.5)^{c}
Live woody cover	<0.001	32.6(18.4)^{a}	37.9(13.1)^{a}	48.8(14.2)^{ab}	55.4(15.2)^{bc}	50.5(12.5)^{b}	59.6(11.3)$^{\mathbf{bc}}$	55.2(18.1)^{bc}	67.7(9.8)^{c}
Dead herbaceous litter mass	^{A}0.003	0.7(0.9)^{a}	0.6(0.8)^{a}	0.6(0.4)^{a}	1.0(1.0)^{ab}	1.1(1.0)^{a}	0.9(0.5)^{ab}	1.6(1.2)^{ab}	2.2(1.8)^{b}
Live herbaceous mass	–	1.2(1.6)^{a}	1.2(1.2)^{a}	1.2(1.4)^{a}	0.8(1.5)^{a}	1.0(1.5)^{a}	0.5(0.4)^{a}	0.8(0.5)^{a}	1.1(1.7)^{a}
Live herbaceous cover	^{A}0.016	18.6(14.6)^{ab}	25.8(17.0)^{b}	22.9(16.2)^{ab}	13.4(16.1)^{a}	27.3(18.2)^{b}	23.1(15.5)^{ab}	18.2(9.4)^{ab}	16.6(16.1)^{ab}

[A]Kruskal–Wallis test used due to failed assumptions of ANOVA.

Table A2. Post hoc comparison of crushed, re-masticated and masticated plus burned treatments by time since treatment (TST)

ANOVA results presented with mean and standard deviation (s.d.) for mass (Mg ha^{-1}), cover (%), height (m) and depth (cm) by fuel component. Values sharing superscripts (a, b, c, d) within rows are not statistically different ($P > 0.05$)

		Crushed			Re-masticated				Masticated & burned	
TST (year)		2	4		1	3	4		1	2	5
ANOVA (*p*)		(*n* = 6)	(*n* = 6)	(*p*)	(*n* = 1)	(*n* = 7)	(*n* = 6)	(*p*)	(*n* = 9)	(*n* = 5)	(*n* = 5)
1-h mass	–	4.7(2.8)	3.4(3.4)	–	5.1^{a}	2.3(0.9)^{a}	2.7(2.1)^{a}	–	0.4(0.6)^{a}	0.6(0.8)^{a}	0.9(1.1)^{a}
10-h mass	–	12.9(7.3)	11.3(9.9)	–	13.0^{a}	3.4(1.8)^{a}	6.2(6.8)^{a}	–	0.6(0.7)^{a}	1.5(1.4)^{a}	1.5(1.8)^{a}
100-h mass	–	11.1(9.9)	7.0(9.7)	–	0.0^{a}	2.0(2.4)^{a}	2.8(1.8)^{a}	–	0.0(0.0)^{a}	0.8(1.9)^{a}	1.0(1.4)^{a}
1000-h mass	–	0.7(1.6)	3.2(5.0)	–	0.0^{a}	0.2(0.6)^{a}	7.1(13.4)^{a}	n/a	0.0(0.0)^{a}	0.0(0.0)^{a}	0.0(0.0)^{a}
Downed woody mass	–	29.3(18.9)	24.9(26.4)	–	18.2^{a}	7.9(4.2)^{a}	18.9(17.2)^{a}	–	1.1(1.2)^{a}	3.0(2.6)^{a}	3.5(3.9)^{a}
Downed woody depth	–	13.7(4.2)	10.1(5.4)	–	5.4^{a}	4.0(1.2)^{a}	6.9(12.2)^{a}	–	1.8(0.7)^{a}	1.6(0.6)^{a}	1.9(0.7)^{a}
Downed woody cover	0.007	51.8(9.5)	30.5(12.1)	0.014	85.5	28.6(13.0)^{a}	27.3(17.1)^{a}	–	4.7(4.6)^{a}	17.2(16.1)^{a}	11.9(11.6)^{a}
Live woody mass	0.023	4.8(1.7)	10.3(5.1)	–	7.2^{a}	5.2(3.7)^{a}	7.2(4.8)^{a}	<0.001	2.8(1.3)	7.3(1.5)	11.9(3)
Live woody height	^{A}0.037	0.7(0.2)	0.9(0.2)	^{A}0.007	1.2^{a}	1.2(0.2)^{a}	0.7(0.1)	^{A}0.007	0.7(0.1)	1.2(0.1)^{a}	1.0(0.4)^{a}
Live woody cover	0.001	30.4(9.9)	55.0(9.8)	–	46.5^{a}	41.5(21.1)^{a}	39.0(14.7)^{a}	^{A}0.010	31.0(8.9)^{a}	48.1(10.9)^{ab}	62.5(23.9)^{b}
Dead herbaceous litter mass	–	0.4(0.4)	0.4(0.3)	–	2.1^{a}	0.6(0.2)^{a}	1.1(0.9)^{a}	<0.001	0.1(0.1)^{a}	0.8(0.7)^{b}	0.3(0.3)^{ab}
Live herbaceous mass	–	0.4(0.3)	0.6(0.5)	–	0.2^{a}	1.4(1.0)^{a}	1.1(1.7)^{a}	0.013	2.1(1.8)^{a}	1.5(1.0)^{ab}	0.4(0.4)^{b}
Live herbaceous cover	–	33.8(21.2)	38.1(9.8)	–	30.3^{a}	39.9(16.9)^{a}	24.9(17.8)^{a}	–	43.8(16.0)^{a}	37.6(19.2)^{a}	26.5(34.2)^{a}

[A]Kruskal–Wallis test used due to failed assumptions of ANOVA.

Table A3. Post hoc comparison of proportions of treatment to control by treatment type and time since treatment

ANOVA p values presented with *mean* and standard deviation (s.d.). Values sharing superscripts (a, b, c, d) are not statistically different ($P > 0.05$)

ANOVA (p)		Time-since-treatment year 1	2	3	4	5	6	7	8
Crushed			($n = 6$)		($n = 6$)				
Live woody cover	0.001		0.34(0.12)		0.62(0.06)				
Live woody height	0.045		0.34(0.08)		0.50(0.16)				
Live woody mass	0.006		0.28(0.10)		0.62(0.22)				
Live herbaceous cover	–		10.34(11.03)^{a}		13.34(8.52)^{a}				
Masticated		($n = 11$)	($n = 29$)	($n = 18$)	($n = 26$)	($n = 36$)	($n = 7$)	($n = 9$)	($n = 12$)
Live woody cover	<0.001	0.38(0.25)^{a}	0.47(0.17)^{ab}	0.53(0.15)^{abc}	0.61(0.16)^{cd}	0.58(0.13)^{bcd}	0.72(0.21)^{cd}	0.60(0.21)^{abcd}	0.73(0.9)^{d}
Live woody height	0.001	0.35(0.18)^{a}	0.45(0.16)^{ab}	0.49(0.19)^{ab}	0.50(0.13)^{b}	0.56(0.14)^{b}	0.53(0.07)^{ab}	0.47(0.15)^{ab}	0.56(0.15)^{b}
Live woody mass	0.003	0.27(0.25)^{b}	0.42(0.29)^{b}	0.43(0.31)^{ab}	0.65(0.29)^{a}	0.53(0.31)^{ab}	0.64(0.22)^{ab}	0.33(0.17)^{b}	0.50(0.25)^{ab}
Live herbaceous cover	–	10.67(5.70)^{a}	10.88(9.05)^{a}	14.79(13.96)^{a}	11.19(11.62)^{a}	16.33(14.16)^{a}	7.03(5.25)^{a}	8.80(7.78)^{a}	5.35(6.74)^{a}
Re-masticated		($n = 1$)		($n = 7$)	($n = 4$)				
Live woody cover	–	0.50(0.00)^{a}		0.48(0.26)^{a}	0.44(0.11)^{a}				
Live woody height	–	0.51(0.00)^{a}		0.58(0.22)^{a}	0.32(0.12)^{a}				
Live woody mass	–	0.56(0.00)^{a}		0.36(0.39)^{a}	0.40(0.37)^{a}				
Live herbaceous cover	–	31.30(0.00)^{a}		22.45(23.91)^{a}	14.19(8.75)^{a}				
Masticated & burned		($n = 9$)	($n = 5$)			($n = 5$)			
Live woody cover	^{A}0.012	0.37(0.10)^{a}	0.55(0.19)^{a}			0.88(0.31)			
Live woody height	<0.001	0.35(0.06)	0.49(0.10)			0.70(0.11)			
Live woody mass	<0.001	0.21(0.09)	0.56(0.17)			1.20(0.22)			
Live herbaceous cover	0.002	29.73(13.63)^{a}	15.83(5.84)^{a}			5.15(5.82)			

[A] Kruskal–Wallis test used due to failed assumptions of ANOVA.