Final Report JFSP Project Number 10-1-01-23

Project Title: Effectiveness and Effects of Mastication Fuel Treatments in Non-forested Vegetation of Southern California

Principal Investigator:

Dr. Jon E. Keeley, Research Ecologist, USGS Western Ecological Research Center, 47050 General's Highway, Three Rivers, CA 93271; Phone: (559) 565-3170; e-mail: jon_keeley@usgs.gov

Co-Principle Investigators:

Dr. David R. Weise, Supervisory Research Forester, USDA Forest Service, Pacific Southwest Research Station, Forest Fire Laboratory, Riverside, CA 92507; Phone (951) 680-1543; e-mail: dweise@fs.fed.us

Teresa Brennan, Ecologist, USGS Western Ecological Research Center, 47050 General's Highway, Three Rivers, CA 93271; Phone: (559) 565-3172; e-mail: tjbrennan@usgs.gov

This final report details findings and accomplished deliverables.

This research was sponsored in part by the Joint Fire Science Program. For further information go to www.firescience.gov

Acknowledgements:

Field assistance by Chelsea Morgan (Team lead), Callen Huff, Richard Mansfield, Graydon Dill, Anthony Baniaga, and Warren Reed was indispensable to this study, as was the logistical help from the Riverside Fire Lab (USFS), Marti Witter (NPS), Anne Pfaff (USGS), Kim Bollens (USGS), and Wendy Boes (AMSET). We acknowledge cooperation of USDA Angeles, Cleveland, Los Padres, and San Bernardino national forests with special thanks to Steve Davis, Michael Strawhun, Fred Montes, Karen Bauman, Diane Travis, Scott Lowden, Dan Felix, Lauren Blake, David Kelly, Jacob Gipson, Gordon Martin, Frank Romero, and Stephen Fillmore.

JOINT FIRE SCIENCE PROGRAM
FIRESCIENCE.GOV
Research Supporting Sound Decisions

Abstract

Mechanical fuel treatments are a pre-fire strategy for reducing wildfire hazard at the wildland-urban interface. At present, most of our information on their effectiveness and effects comes from forested systems. Our objectives were to quantify changes in chaparral fuel structure following mechanical treatment and to assess treatment longevity. We compared mastication, re-mastication, mastication plus burning, and crushing treatments over an 8-year post-treatment period in southern California. Results show that initial treatment reduces canopy height and live-woody cover by two-thirds, while concentrating downed-woody fuels at the surface. Surface loads were significantly different between treatment types in composition, depth, and percent cover, while herbaceous fuels increased significantly across all treatments. Woody vegetation regrowth was rapid in all treatments and reached approximately 50% of the untreated control cover, height, and mass by post-treatment year four. This suggests that treatment longevity and effectiveness are relatively short-term in chaparral dominated landscapes. These results coupled with the associated drawbacks of these treatments, leave concern for their widespread use across landscapes. The consequences of not having a full understanding of these treatments are potentially serious, posing a risk to human safety, as well as natural resources, and warrant the need for further research.

Mastication treatment in mixed chaparral along the Camino Cielo Divide on the Los Padres National Forest (Photo credit: Fred Montes).

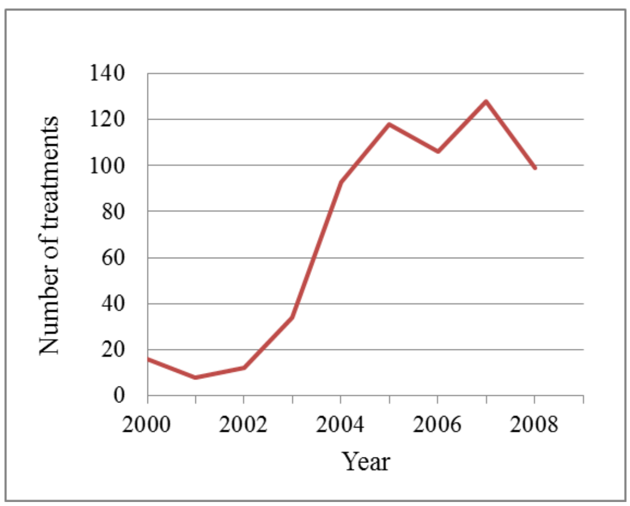
Background and Purpose

A major challenge facing land management agencies is how to manage wildlands in ways that minimize community vulnerability to wildfires and maintain 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 shrubland ecosystems prone to periodic high intensity crown fires. Losses of property and lives in the urban environment of California greatly exceed that of any other region in the country; for example, in the last 35 years 12 of the 15 most costly fires have occurred in California, and mostly in southern California (Miller 2007). There is growing concern in the region because in the last 6 years there have been 5 megafires over 50,000 ha (~125,000 acres), a rate of burning not observed in any other period since record keeping began (Keeley and Zedler 2009).

An important part of managing the wildfire risk in southern California has always included fuel treatments in both the wildland and the wildland-urban interface. In the latter half of the last century management philosophy was dominated by the idea that prescription burning on a rotational basis was one means of solving this problem. However, in recent decades it has become evident that the magnitude of area in need of treatment, constraints on implementation of prescription burning, and dangers of escaped fires adjacent to populated urban environments, has turned the tide towards more focused attention on strategic sites using mechanical fuel treatments (Jones et al. 2008).

Although mastication has been part of fuels management in southern California chaparral for more than 30 years (Roby and Green 1976), in the last decade mastication, chipping and crushing have been used much more extensively than in the past. 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 (Fig. 1). The rate of treatment application on these forests is expected to continue or even accelerate over the next several years.

Fig. 1. Mechanical fuel treatments on federal lands in southern California from 2000-2008. Data compiled from the USGS Southern California Fuel Treatment Data Set available at http://www.cafiresci.org.



On these forests the vast majority of mastication treatments have been conducted in chaparral shrublands. The goal of these treatments is to reduce fuel loads to a target level of 4 tons per acre. On some sites this can be accomplished by mastication alone but on other sites it requires coupling mastication with prescription burning. In addition to these treatments a large number of sites have involved other forms of shredding biomass such as chipping, mowing and crushing. In this rugged terrain the most appropriate treatment application is not always clear and managers would benefit from a better understanding of the best management practices for particular fuel types and topography.

This study was initiated in response to a letter from a battalion chief on the Cleveland National Forest to the JFSP expressing need for understanding effects and effectiveness of mastication and related mechanical treatments (Tim Svedberg, email 2 Oct 2009). Despite the widespread use, particularly in non-forested systems we lack best management practices for the application of these techniques, primarily due to a lack of research on effectiveness and effects in non-forested systems. At present, essentially all of our information on the effectiveness and effects of mastication treatments comes from forested systems outside of southern California. The differences in fire regimes between forested and non-forested ecosystems suggests caution in extrapolating results from one system to the other, particularly with regards to fuel treatment effects and effectiveness.

The specific aim of this project was to help southern California managers identify vegetation management goals and resource trade-offs on non-forested landscapes by quantifying 1) fuel load and structure for various treatments with and without prescribed fire 2) treatment intervals for various age class management, and 3) vegetation recovery and community response.

Study Description and Location

The purpose of this study was to quantify changes in chaparral fuel structure following mastication and other mechanical treatments to determine treatment longevity, as well as to assess ecological effects on community composition. Our primary objectives were to:

Objective 1: Determine fuel bed structure and composition of masticated and crushed treatments and compare to sites with follow-up treatments of prescribed fire and repeat mastication.

Objective 2: Assess the long-term effectiveness of mastication, crushing, repeat mastication, and mastication plus burning by quantifying vegetation response and recovery on treated sites and comparing to untreated vegetation.

Objective 3: Assess potential effects on plant and soil resources by quantifying native and non-native plant species in treated and untreated areas; comparing changes in plant community composition; and comparing soils characteristics in treated and untreated sites.

Objective 4: Create a digital photo series of mechanical treatments from a range of fuel loads in chaparral across the four southern California National Forests for use by managers as a quick reference for fire management planning.

A total of 63 fuel treatments located across the four southern California National Forests were used for this study (Fig. 2). Mastication was the most predominant treatment type with crushing, re-mastication, and mastication plus prescription burning being less common and only available on one or two forests per treatment type (Table 1). Individual treatment study site locations were chosen using the random point generator option in ArcGIS 10.0 software and control sites were located at the boundary of untreated vegetation at a location that best represented the pre-treatment vegetation type.

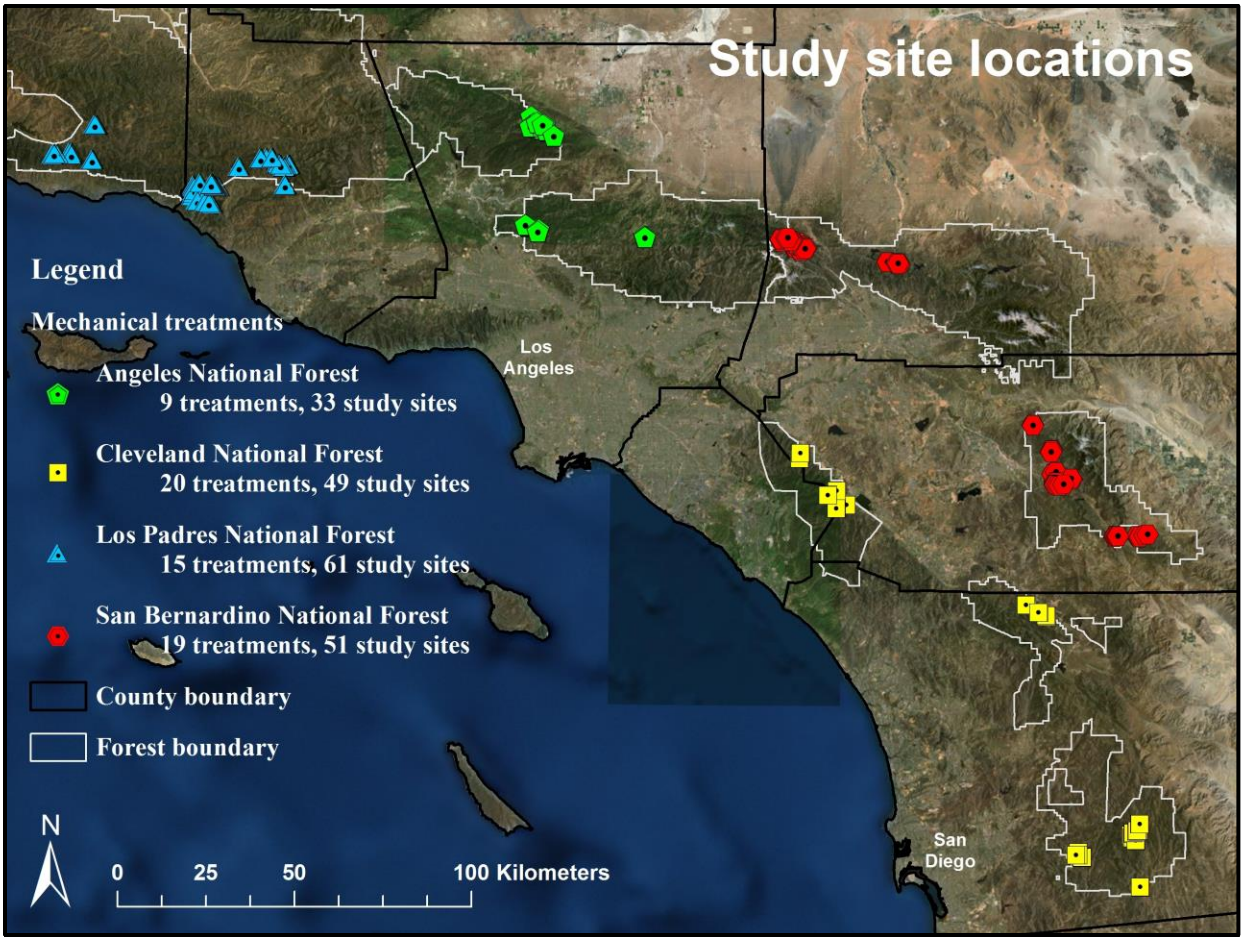


Fig. 2. Study site locations within mechanical treatments on the four southern California national forests.

Table 1. Study site characteristics summarized by treatment type. Vegetation communities were classified as either chamise dominated (CD) or mixed chaparral (MC).

Treatment type	Study sites (#)	Vegetation communities (# and type)	Age at time of treatment (years)	Elevation (m)	Slope (deg)
Crushing	12	9 CD, 3 MC	35-53	1187-1363	23-50
Mastication	149	42 CD, 107 MC	7-64	230-2267	2-45
Re-mastication	14	3 CD, 11 MC	19-38	309-1598	7-37
Mastication plus prescription burning	19	6 CD, 13 MC	16-38	832-1710	5-43

Field sampling of treatments and controls was conducted in the spring and summer of 2011 and 2012. Each study site consisted of a 10 x 100 m treatment plot placed across the slope and a 2 x 100 m control plot placed along the edge of untreated vegetation. Species composition, cover and density were acquired from vegetation surveys and fuel load and structure data were determined from destructive plot-based fuel surveys (Kane 2007). Disturbances to soils and substrate from animals, erosion, and equipment were also quantified in cover surveys. A subset of treatment sites were chosen that represented a range of fuel loads across the four forests and photographed for incorporation into a fuel photo series for mechanical treatments in chaparral. Each site was photographed at a distance of 9.14 m (30 ft.) from a replicated standard National Fuel System pole (Maxwell and Ward 1980) that was placed within the study site at a location representing average fuel loading (Fig. 3.).

Fig. 3. Two year old mastication treatment in mixed chaparral on the San Bernardino National Forest. The edge of untreated vegetation can be seen in the upper left corner.

Key Findings and Relationship to other Recent Studies

Mechanical treatments have steadily become a primary method for treating fuels in the forest and shrubland ecosystems of southern California. The advantages of using mechanical treatments, such as mastication and crushing are 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 behavior by reducing flame lengths, intensity, and rate of spread of fire (Hudak et al., 2011; Kreye et al., 2014) 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). This in effect, alters fuel structure, potentially allowing improved fire fighter access and suppression efficacy (Syphard et al., 2011). Results from our study found that mechanical treatments do significantly alter fuel structures in chaparral dominated landscapes by re-arranging live canopy fuels into a compacted layer of dead and downed woody fuels at the soil surface. The longevity of these fuel alterations, however, appears limited by the rapid regrowth of resprouting shrub species in these ecosystems.

Mastication

The initial impact of mastication on fuel components in chaparral was a two-thirds reduction in stand height and live woody cover in comparison to untreated controls at post treatment year one (Fig. 4). Downed woody fuels were concentrated into densely compacted fuel beds averaging 5 cm in depth with a corresponding average cover and mass of 55% and 34 Mg/ha, respectively (Fig. 5). These values are within the range of results observed by Kane et al. (2006 and 2009) in masticated *Arctostaphylos* spp. and *Ceanothus* spp. stands in northern California where downed woody fuel depths were 3.2-8.0 cm and masses ranged from 15.3-63.4 Mg/ha. Results from Reiner and Decker (2009) in a mix of chaparral dominated and chaparral understory sites in southern California showed similar fuel depths ranging from 3-5 cm, but had substantially higher downed woody masses between 38.1-76.2 Mg/ha. Interestingly, a portion of their study sites overlapped ours in a chaparral dominated mastication treatment on the San Bernardino National Forest. Reiner and Decker surveyed the treatment approximately one year following mastication, whereas we surveyed the treatment five years following mastication. Their results showed an average masticated downed woody fuel depth of 3.7 cm with a corresponding cover of 73% and mass of 28.4 Mg/ha. Our results for the same treatment four years later were 3.4 cm, 34%, and 7.8 Mg/ha, respectively, which is consistent with our overall results showing a decrease in downed woody cover, depth, and mass over time in chaparral stands.

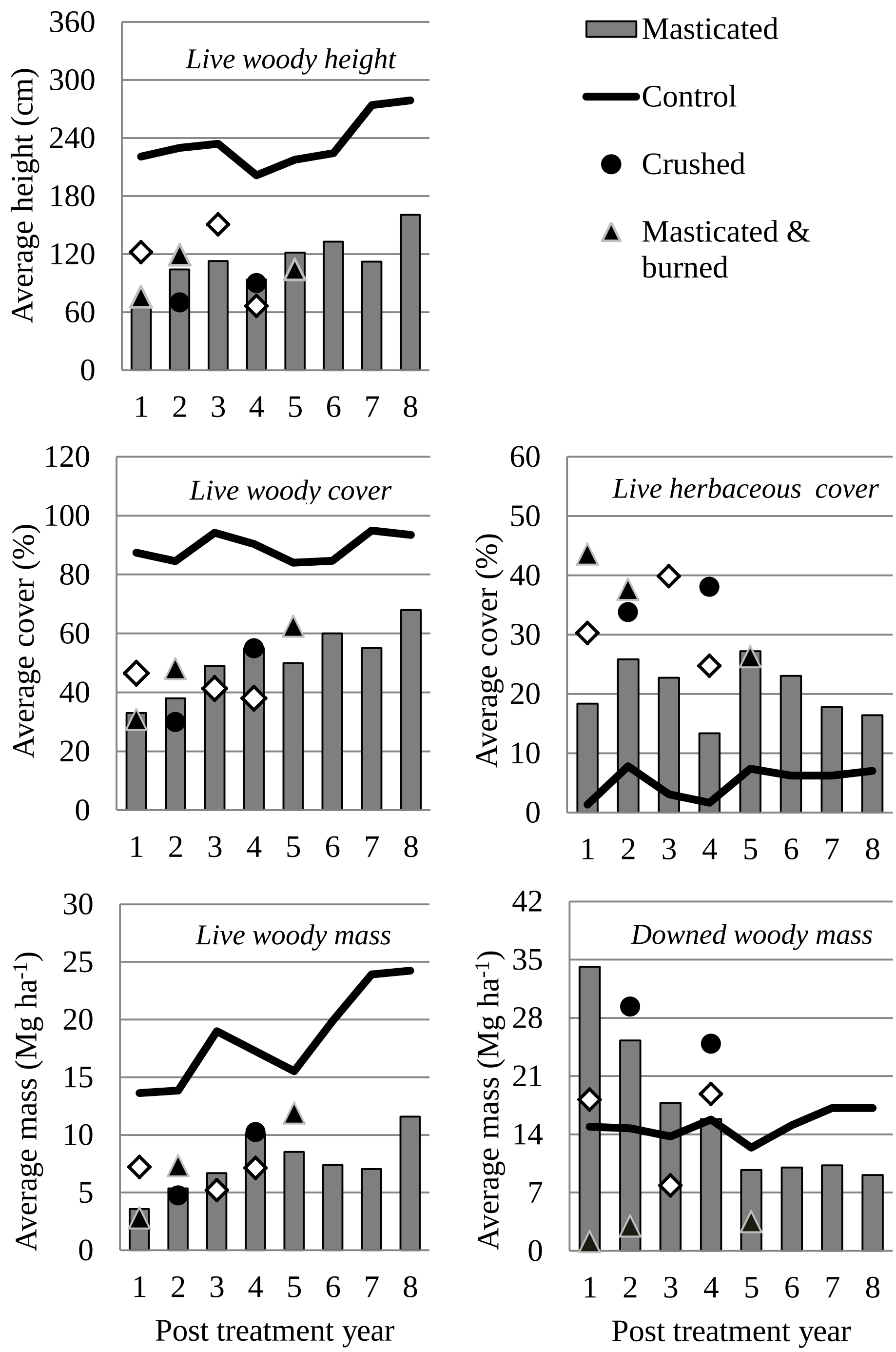


Fig. 4. A comparison of fuel components between treatments and untreated controls by post treatment year.

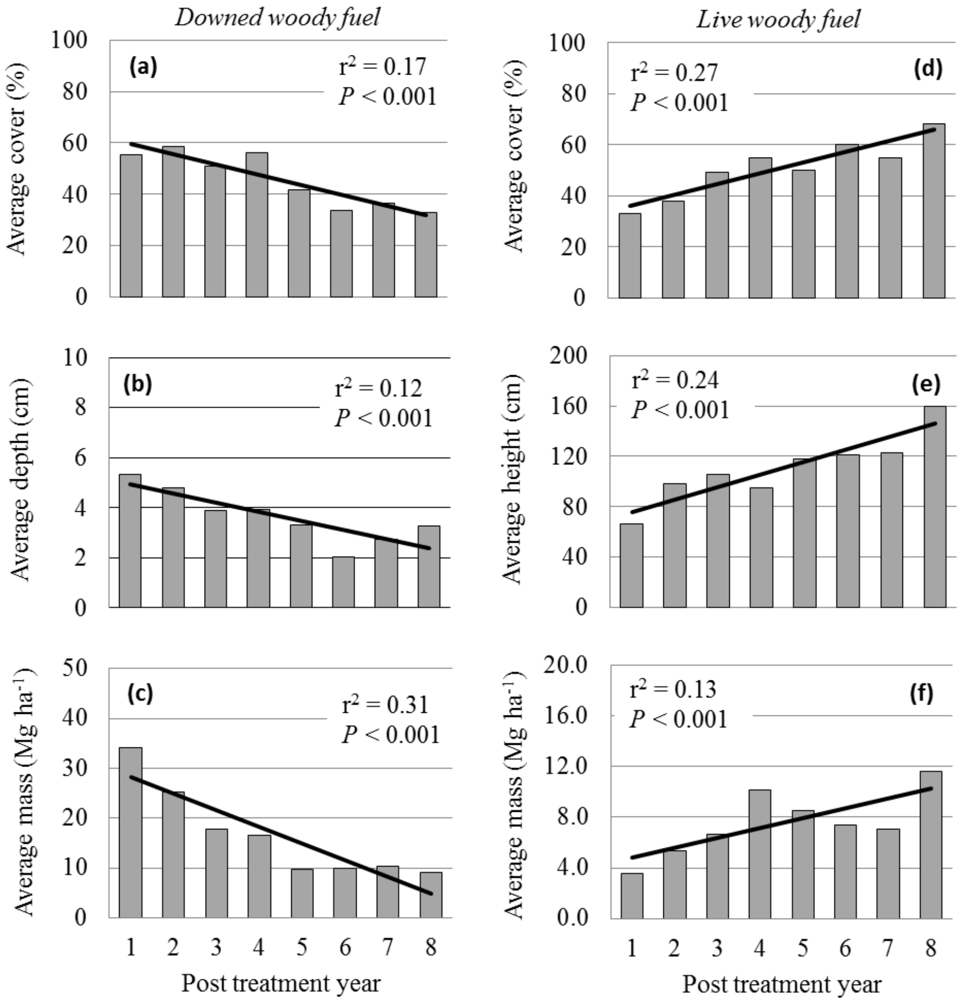


Fig. 5. Average cover, depth, and mass of downed woody fuels (a, b, c) and average cover, height, and mass of live woody fuels (e, f, g) in masticated treatments by post treatment year; r^2 and *P* values are presented from bivariate regression analyses of all masticated study sites (n = 149).

The process of mastication, which breaks and shreds woody vegetation into small fractured particles, changes the proportions and distributions of downed woody fuels into various fuel classes. Results from a number of studies have found that the proportions of downed 1, 10, 100, and 1000 hour fuels, following mastication treatment, vary by the species being masticated, pre-treatment stand conditions, and the type of machinery used (Stephens and Moghaddas 2005; Glitzenstein et al., 2006; Kane et al., 2009; Reiner et al., 2009; Kreye 2012; Brewer et al., 2013). Proportions of the total downed woody fuel load by fuel class in our study were very similar to those observed by Kane et al. (2009) in chaparral dominated stands, which were 30%, 54%, 13%, and 3% in comparison to our results of 28%, 52%, 17%, and 3% for 1, 10, 100, and 1000 hour fuels, respectively (Fig. 6). Results from Reiner and Decker (2009) were also within the same range with fuel class proportions of 20-36%, 54-59%, 6-23%, and 0-1%, respectively.

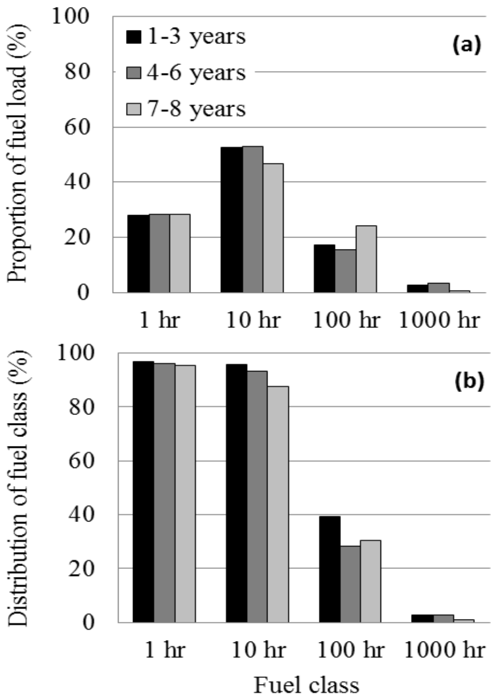


Fig. 6. Proportion of total fuel load by fuel class (a) and distribution of individual fuel classes (b) by post treatment age for masticated treatments. No significant differences were found between age classes using Mann-Whitney tests.

Our results also show that mastication significantly alters fuel structure by substantially increasing live and dead herbaceous fuels. In chaparral dominated sites, mastication removes most, if not all of the canopy cover, thereby aiding the germination of herbaceous plants. In older untreated stands the presence of herbaceous plants was minimal with herbaceous plants having an average cover of 3.6% (Fig. 4). Masticated stands, conversely, had an average herbaceous cover of 21.6% and an average herbaceous mass 1.0 Mg/ha. A study by Kane et al. (2010) in chaparral understory reported an increase in average herbaceous fuel cover from 14% in untreated stands to 26% in masticated sites, which is line with our observations. Potts and Stephens (2009) looked at non-native herbaceous responses in chamise dominated chaparral following spring and fall mastication treatments and also reported a significant increase in herbaceous fuels following treatment.

Longevity of mastication treatments

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 require an increasingly larger budget (NIFC 2013). A complication in determining treatment longevity is that it is dependent on individual vegetation management objectives. Personal communications with individual fuel managers on the four southern California national forests revealed widely different management objectives for the 63 treatments we studied. For instance, the goal for one forest was to maintain chaparral in a seral stage, while the goal for another was to type convert the treatment area.

Despite these differing objectives, our results show that recovering live woody fuel is the most important factor determining treatment longevity. Chaparral ecosystems, which are prone to periodic wildfires, have a high number of species that are able to re-sprout from basal underground structures when damaged. This ability allows for the rapid recovery of live woody fuels within masticated treatments and is a primary limiting factor of their long term effectiveness (Schwilk et al., 2009; Kane et al., 2010; Kreye et al., 2012). A study by Kreye et al. (2013) showed that fires were less driven by surface fuels as soon as recovering shrubs emerged over the masticated fuel bed. Our results from a mix of chaparral types showed recovering live woody fuels emerging above the masticated fuel bed in post treatment year one. At post treatment year two, masticated stands had an average live woody cover and height that was 45% of the average cover and height of untreated controls, with a live woody mass that was 39% of the control mass (Fig. 4). By post treatment year eight the average height, cover, and mass of live woody fuels was near the low end of the range of average values observed for a variety of untreated chaparral vegetation types (Table 2). These results suggest that treatment longevity and effectiveness are relatively short-term in chaparral dominated landscapes. The actual longevity of any given treatment, however, will depend upon the individual species present and the pre-treatment site conditions.

Table 2. Untreated control sites characteristics summarized by vegetation type. Average live and downed woody fuel masses were estimated using fuel models.

Treatment Type	Study Sites (#)	Age (years) Avg. (Range)	Height (m) Avg. (Range)	Live woody cover (%) Avg. (Range)	Live herbaceous cover (%) Avg. (Range)	Live woody mass (Mg/ha) Avg. (Range)	Downed woody mass (Mg/ha) Avg. (Range)
Ceanothus	23	27	3.0	99	4	27.8	14.6
		(19-36)	(1.6-4.9)	(87-127)	(0-34)	(11.2-37.4)	(5.2-18.4)
Chamise	53	36	1.8	79	5	14.0	7.5
		(8-69)	(0.9-2.8)	(31-102)	(0-43)	(6.3-25.1)	(5.6-9.9)
Chamise/ Redshank	17	43	2.3	82	7	11.9	8.0
		(26-68)	(1.8-2.9)	(62-99)	(0-27)	(6.5-15.2)	(6.7-9.9)
Lower montane mix	74	39	2.1	91	3	16.0	19.2
		(19-60)	(1.1-4.1)	(53-119)	(0-26)	(3.8-29.8)	(5.2-26.4)
Manzanita	17	41	1.8	91	0	18.7	20.2
		(27-68)	(0.9-2.7)	(80-99)	(0-3)	(13.9-26.0)	(15.5-28.9)
Scrub oak	10	42	2.9	98	2	18.3	20.4
		(27-56)	(1.4-4.8)	(81-109)	(0-14)	(12.1-26.4)	(15.5-25.1)

Comparison of mastication and crushing treatments

A variety of mechanical treatments have long been used to alter fuel structures in an effort to mitigate and control wildfires on the landscape. Fuel treatments in southern California, however, have not always been easy to implement due to the steepness of terrain. In recent decades, both crushing and mastication have become available to treat steep slopes that were previously inaccessible to machinery. The methods by which fuels are altered by these two techniques are different and as a result alter fuel structures in different ways. Crushed treatments in our study had significantly deeper downed woody depths than masticated treatments with slightly higher average masses (Fig. 7) and a significantly higher portion of larger fuel classes (Fig. 8). Mastication treatments, conversely, had a significantly higher proportion of finer 1 and 10 hour fuels and a significantly higher percent cover of downed woody fuel (Fig. 9). These differences appear to be directly related to the process of the treatment with crushed fuels being compacted in place, whereas masticated fuels are shredded and spread over the surface. Crushed treatments will likely retain the downed woody surface fuels on site longer than mastication treatments, which could lead to differences in fire behavior between the two treatments. Herbaceous fuels, which were significantly taller and had more cover in crushed treatments, may also exacerbate these differences.

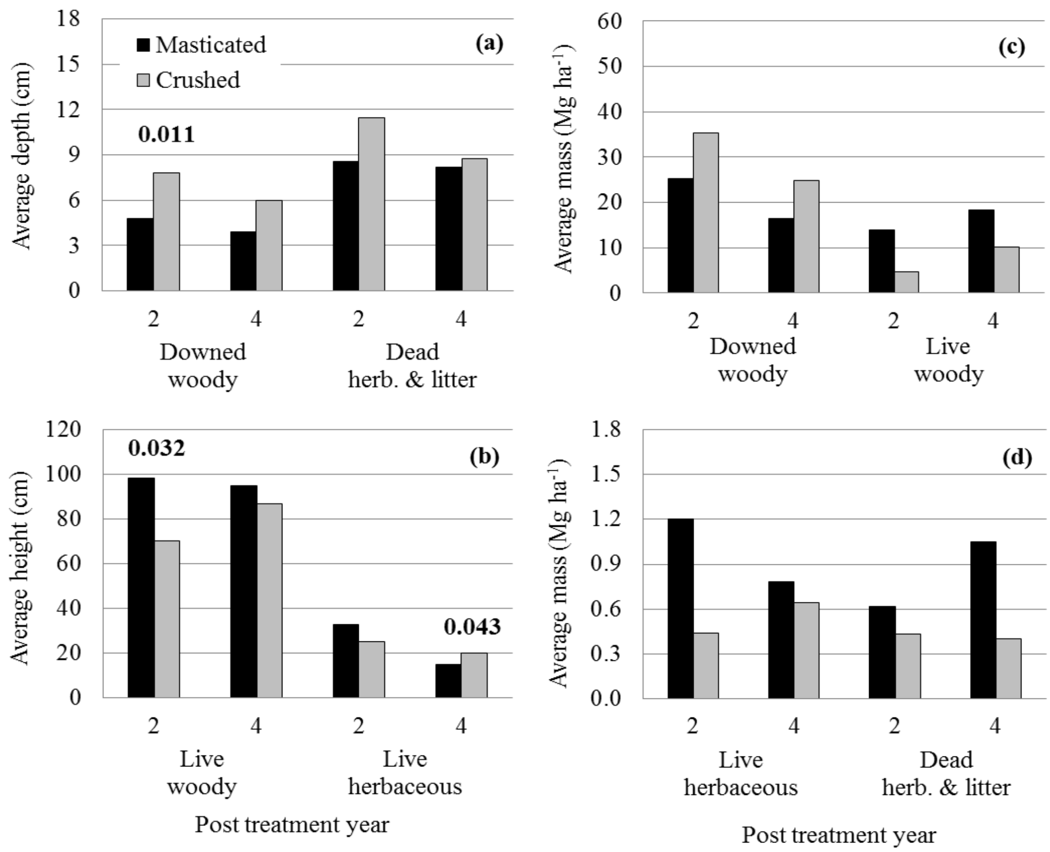


Fig. 7. Average depth of downed woody and dead herbaceous fuels (a), average height of live woody and live herbaceous fuels (b), average mass of live woody and downed woody fuels (c), and average mass of live herbaceous and dead herbaceous fuels and litter (d) for masticated and crushed treatments at 2 and 4 years post treatment. Mann-Whitney *P* values presented for years with significant differences between treatments (two-tailed tests).

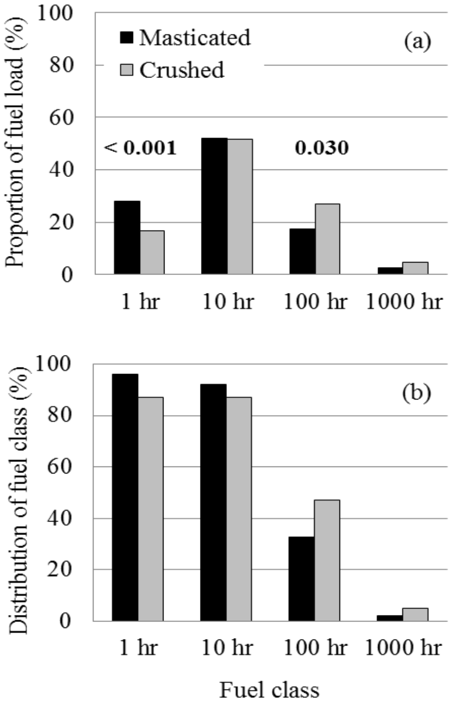


Fig. 8. Proportion of total fuel load by fuel class (a) and distribution of individual fuel classes (b) for masticated and crushed treatments. Mann-Whitney *P* values presented for fuel classes with significant differences between treatments (two-tailed tests).

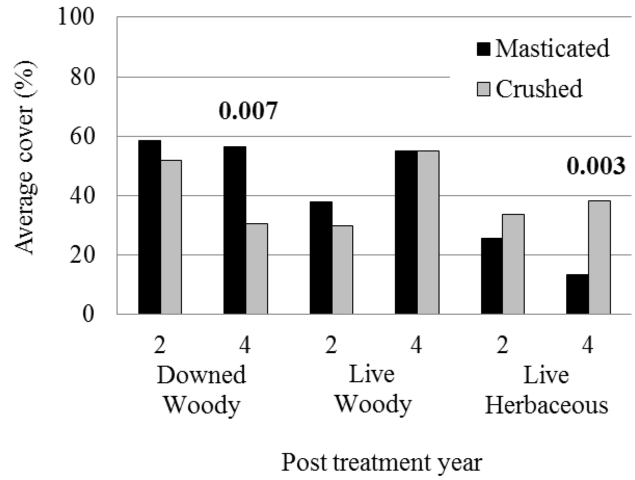
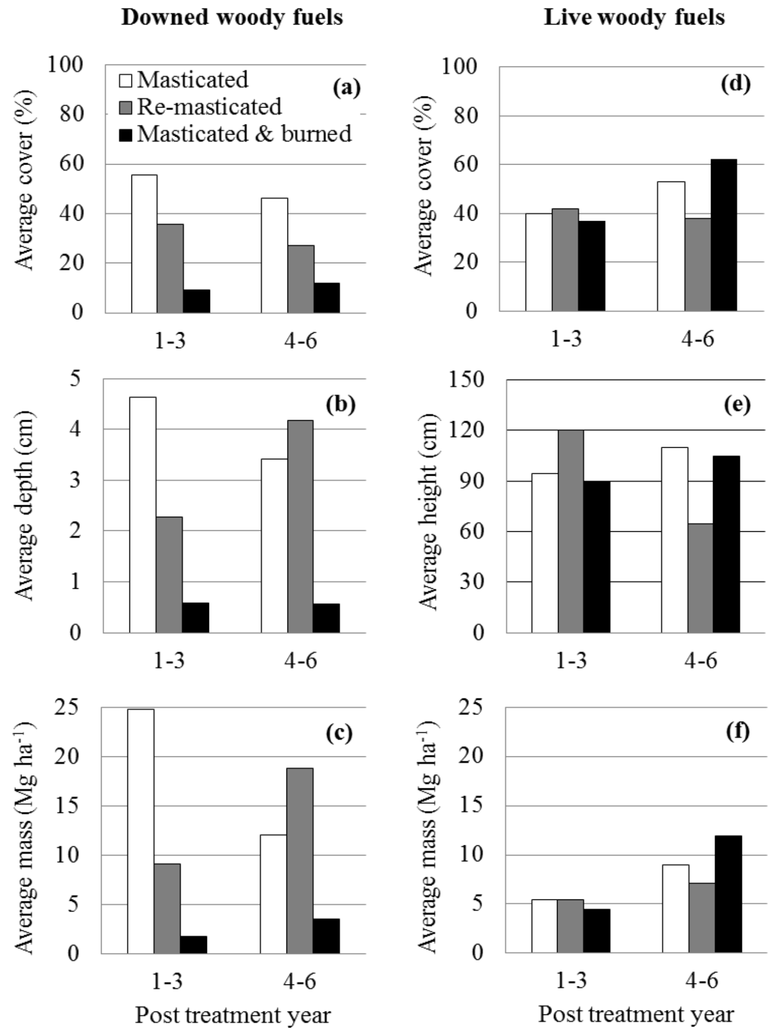


Fig. 9. Average percent cover of downed woody, live woody and live herbaceous fuels for masticated and crushed treatments at 2 and 4 years post treatment. Mann-Whitney *P* values presented for years with significant differences between treatments (two-tailed tests).

Follow-up fuel treatments

In an effort to actually reduce fuels on site, many management plans combine mastication with prescription burning. Often times these burns are never completed due to the constraints on conducting prescription burns. More recently, managers have turned to re-mastication as a follow-up treatment because of the lack of restrictions and ease of implementation. Our results showed that prescription burning significantly reduced downed woody cover, depth, and mass in masticated treatments, as was expected and concentrated the remaining downed woody fuel load into the finer 1 and 10 hour fuels (Fig. 10 & 11). Re-mastication, conversely, increased the average depth and mass of downed woody fuels on site and increased the proportion of fuels in the larger 100 and 1000 hour classes. The recovery of live woody fuels was also different between the two follow-up treatments. Masticated sites that were prescription burned exhibited live woody cover and mass averages that were slightly higher than single entry mastication treatments; whereas re-masticated sites had live woody cover and height averages that were significantly less than single entry mastication treatments. The resultant outcomes between these two follow-up treatment types are undoubtedly different and careful consideration should be exercised in choosing a re-treatment method to obtain specific management objectives.

Fig. 10. Average cover, depth, and mass of downed woody fuels (a-c) and cover, height, and mass of live woody fuels (d-f) in masticated, re-masticated, and masticated & burned treatments by post treatment year.



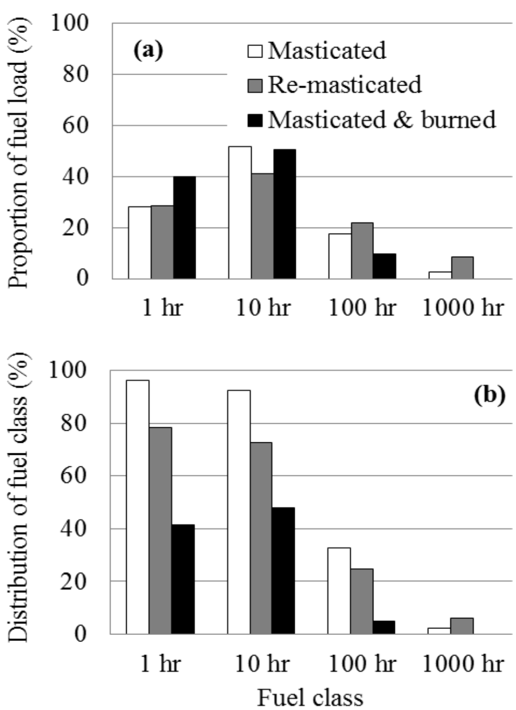


Fig. 11. Proportions (a) and distributions (b) of total fuel load by fuel class for masticated, re-masticated, and masticated & burned treatments.

Vegetative community response and soil disturbance

While the primary objective of a fuel treatment is to alter fuel structure, decreased fuel loading and type conversion are often secondary management goals. Follow-up or repeat treatments are used in an effort to decrease biomass and impose changes in community composition. Findings from our study show that community composition following treatment differs from untreated vegetation and varies by treatment type (Table 3). Shrub cover was significantly different from untreated controls for mastication, crushing, and re-masticated sites across all post-treatment years. A pulse of annual and herbaceous perennial cover was observed following most treatments and was in general, significantly different from controls in the earlier post-treatment years Exotic species cover, conversely, increased in all treatments and was significantly different from controls across all post treatment years. Masticated sites that were prescription burned were the exception and were not significantly different in their life history cover from control sites.

Table 3. Community composition by life history cover for treatments versus control sites. *P* values from two tailed, paired T-tests are presented.

	Mastication versus control				Crushing versus control		Re-mastication versus control		Mastication plus burning versus control		
	1-2 years	3-4 years	5-6 years	7-8 years	2 years	4 years	3 years	4 years	1 years	2 years	5 years
Life history	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*
Shrub cover	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.013**	**< 0.001**	**0.005**	0.778
Perennial/ suffrutescent cover	0.091	**< 0.001**	**< 0.001**	0.083	0.129	**0.002**	**0.032**	**0.03**	0.186	0.062	0.248
Annual cover	**< 0.001**	**0.007**	**< 0.001**	0.342	0.107	1.000	**0.006**	0.059	**< 0.001**	0.12	0.783
Exotic cover	**< 0.001**	**< 0.001**	**< 0.001**	**0.023**	**< 0.001**	**< 0.001**	**0.011**	**0.002**	**0.007**	**0.002**	0.094

We also examined community composition by looking at the relative differences in cover between treatment types and controls (Fig 12). On average the relative cover of shrubs in controls was 90% with annuals, herbaceous natives, and exotics making up the remaining 10%. Each treatment exhibited a shift in species composition but the lasting effect of the change varied by treatment type. Masticated sites exhibited a 34% reduction in relative shrub cover in the first few years following treatment with a subsequent 29% increase in native annual and perennial cover and a 13% increase in exotic cover. By post treatment years 7 and 8 the community composition had shifted closer to the pre-treatment vegetation with only a slight increase in exotic cover and herbaceous species. Crushed treatments exhibited a similar reduction in relative shrub cover, but showed a significant 27-32% increase in exotic cover for post-treatment years 2 and 4. Sites that were re-masticated also showed a greater shift in species composition than single entry mastication sites. At post-treatment year four re-masticated sites had 18% less shrub cover than single entry sites and correspondingly higher native herbaceous and exotic covers of 7% and 11% respectively. Sites that were masticated and then prescription burned exhibited a similar community composition to crushed treatments at 4-5 years post-treatment with a 53% relative cover of shrubs, 8% cover of herbaceous natives, and 39% cover of exotic species.

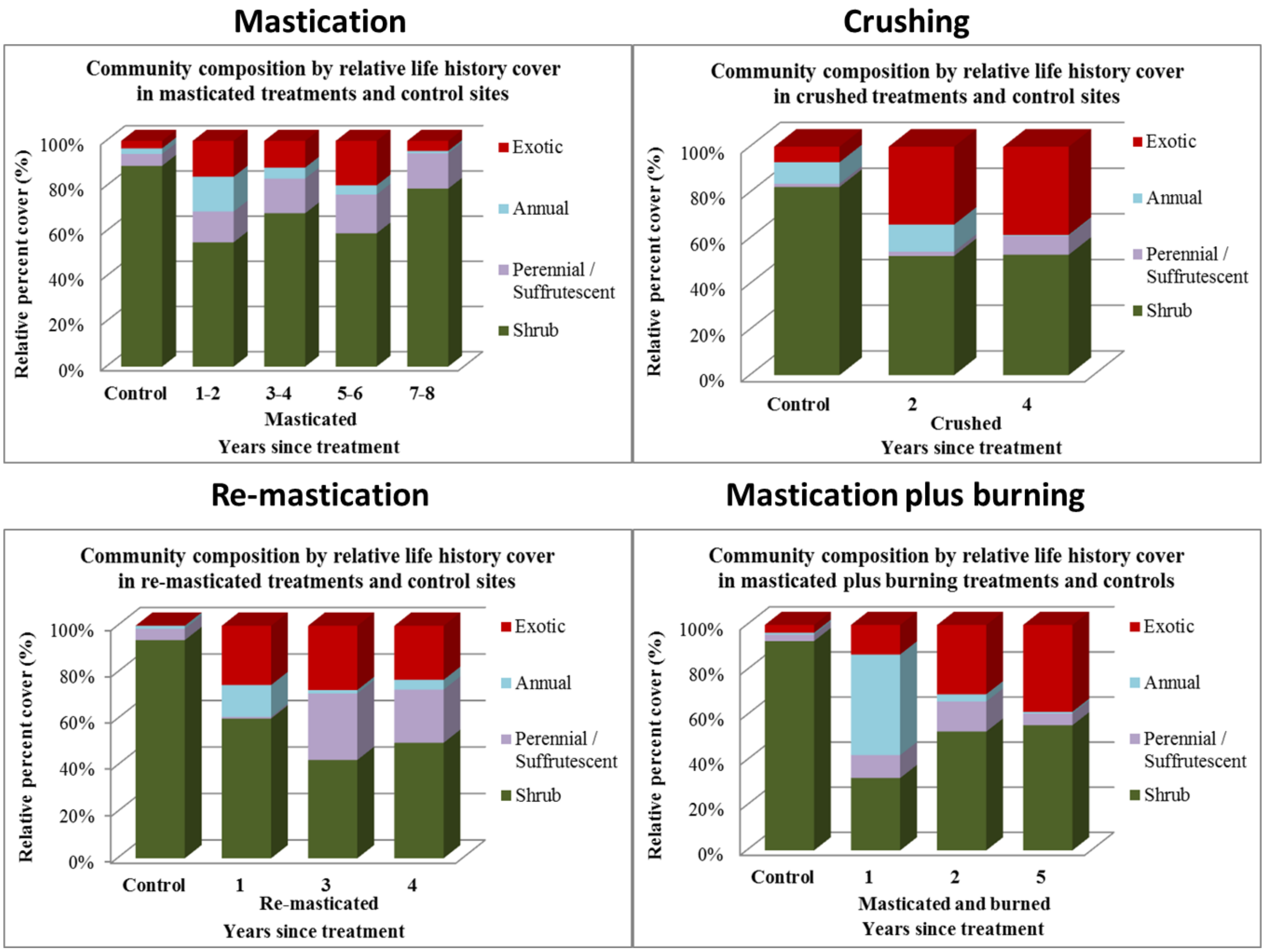


Fig. 12. Community composition in mastication, crushing, re-mastication and mastication plus burning treatments by time since treatment presented as relative cover by life history traits.

These results demonstrate that community composition is significantly changed across all treatment types initially following treatment and suggest the potential for type conversion in sites that are crushed, re-masticated, or masticated and burned. Large shifts in composition from native to exotic species were also evident. In order to better understand the colonization of treatments by exotic species we used regression analyses to look for correlations between native and exotic species in treatments and variables such as pre-treatment stand age, post-treatment year, species diversity and cover in controls, and percent of treatment debris (Table 4).

Table 4. Regression analyses of native and exotic diversity and cover by control age, post-treatment year, diversity and cover of species in controls and treatment debris cover.

	Native species			Exotic species		
Regressions for all treatments combined	+ / -	r^2	*p*	+ / -	r^2	*p*
Diversity vs. control age	-	0.003	0.431	-	**0.023**	**0.036**
Cover vs. control age	-	0.007	0.231	+	< 0.001	0.996
Diversity vs. post-treatment year	-	**0.025**	**0.028**	-	**0.032**	**0.012**
Cover vs. post-treatment year	+	**0.159**	**< 0.001**	-	< 0.001	0.771
Diversity control vs. treatment	+	**0.405**	**< 0.001**	+	**0.049**	**0.002**
Cover control vs. treatment	+	**0.121**	**< 0.001**	+	**0.168**	**< 0.001**
Cover vs. treatment debris cover	-	**0.035**	**0.009**	-	**0.089**	**< 0.001**

Using all treatments combined we observed several differences in relationships when looking at native and exotic species individually. Native species diversity and cover in treated sites was not correlated to pre-treatment stand age but did exhibit correlations with post-treatment year showing a decrease in species diversity over time and an increase in native species cover over time. Exotic species diversity, on the other hand, was correlated with the pre-treatment stand age and exhibited a decrease in the number of exotic species with an increase in pre-treatment stand age. Mechanical treatment in younger stands had a greater diversity of exotic species than treatments in older stands. Exotic species diversity, like native species diversity, decreased with time since treatment. The cover of exotic species in treatments, however, was not correlated to either pre-treatment stand age or post-treatment year. A comparison of species diversity and cover between treatment and controls showed that both native and exotic species diversity and cover were correlated with native and exotic diversity and cover in controls. The relationship between native species diversities in the treatments versus controls, however, was significantly stronger than the relationship observed for exotic species indicating that the increased diversity of exotic species is due to colonization from outside sources (Fig. 13). Downed woody debris on the ground surface from the mechanical treatment was also shown to decrease plant cover for both native and exotic species (Fig. 14). These relationships, however, are quite weak and it is not likely that treatment debris cover will affect vegetation recovery for any length of time.

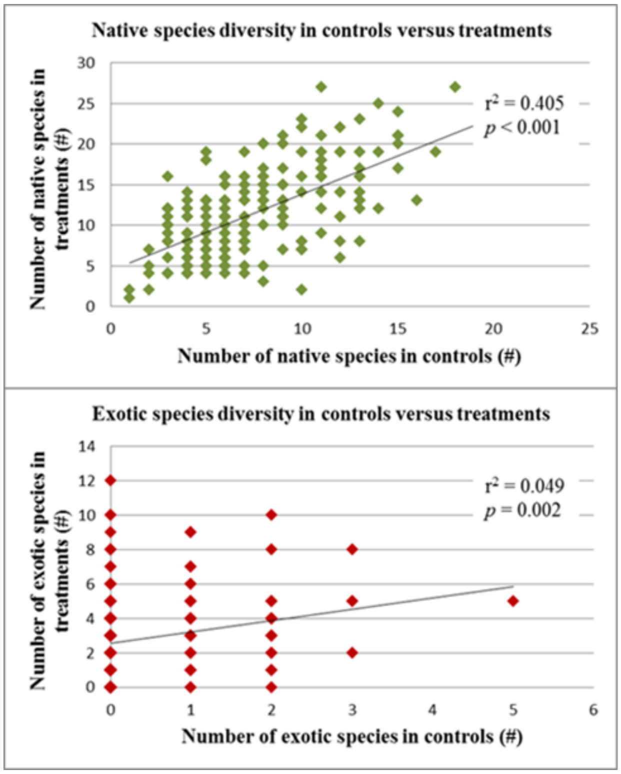


Fig. 13. Exotic species diversity and cover by control age and by the diversity and percent cover of exotic species in controls.

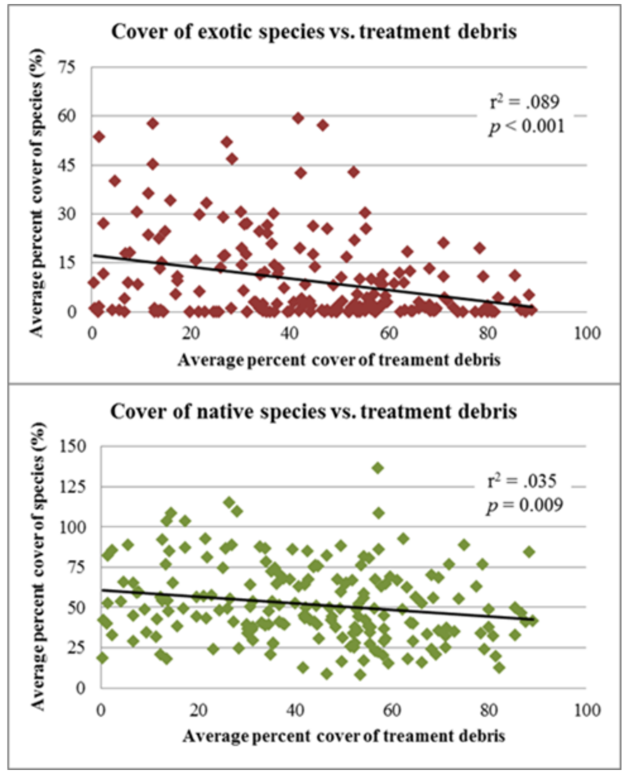


Fig. 14. Cover of native and exotic species versus percent cover of treatment debris on the ground surface.

Another primary concern of natural resource managers is the potential soil disturbance involved with using large machinery to treat fuels. Compaction was an initial concern but it became clear upon visiting a variety of treatments that these sites had looser than normal soils due to the process of roots being pulled above the ground surface. Other concerns we quantified were disturbance by treatment equipment, off highway vehicle (OHV) use, erosion and rilling, and rodent activity (Fig. 15). The average percent of soil disturbance across all treatments was very low with no disturbance exceeding 10%. Re-masticated sites exhibited the highest percent of equipment disturbance which was four times greater than the disturbance observed in single entry mastication treatments and mastication plus burning treatments. OHV use and erosion and rilling were very minimal in all treatments with an average of less than 1% of disturbance observed. A minimal amount of rodent activity was noticed in all treatment types and was higher in treatments with greater equipment disturbance.

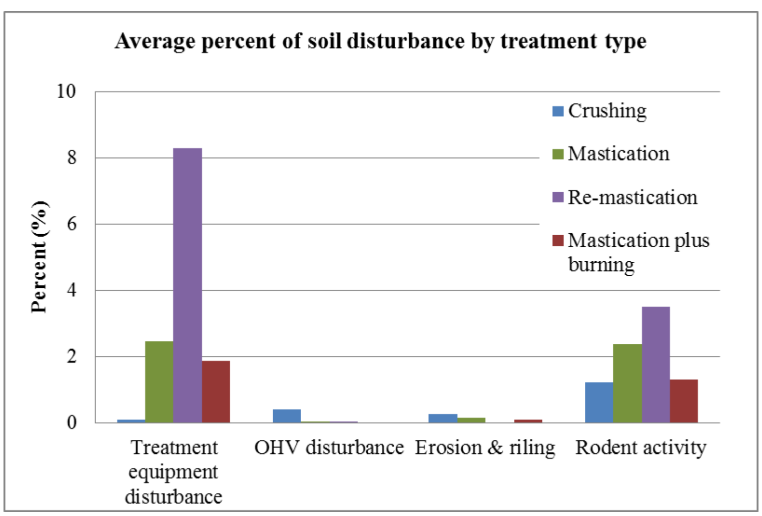


Fig. 15. Soil disturbance by treatment type.

Fuel photo series for mastication treatments

Accurate, complete fuels data are critical for making fuel management decisions and for predicting fire behavior and fire effects. A fuel photo series is a useful reference that allows natural resource managers to quickly quantify fuel and vegetation properties by comparing on site conditions to a series of photo's showing a range of calculated fuel loads within a similar vegetative community. While there are photo series currently available for a wide range of ecosystem types nationwide, there is lack of information available for natural and mechanically treated chaparral. The most likely reason for the lack of information in chaparral is due to the difficulties of collecting fuels data within a dense canopy of shrubs. The guidelines for developing a natural photo series, by Maxwell and Ward (1980), utilize methods that are more conducive to forested or open vegetation types.

Our study, which quantified fuel composition and structure in mechanically treated chaparral, provided a unique opportunity to capture photographs of a range of treatments across a variety of chaparral types on the four southern California national forests. At the end of our second field season, we chose 40 of the 194 study sites we established to be photographed for the photo series. These 40 sites represented a range of fuel loads in mechanically treated chaparral from 11 Mg/ha (5 tons/acre) to 90 Mg/ha (40 tons/acre). Our finished product will be available online at the **California Fire Science Consortium** website at http://www.cafiresci.org. We also intend to incorporate the photos into the National Digital Photo Series available at http://depts.washington.edu/nwfire/dps/. Included below are three examples of the photos and fuels information that will be included.

CALIFORNIA FIRE SCIENCE CONSORTIUM

http://www.cafiresci.org

http://depts.washington.edu/nwfire/dps/

Example 1. Five year old mastication treatment in redshank chamise.

SITE INFORMATION		SITE COVER & HEIGHT		SITE FUEL LOAD	(tons/acre)
State	California				
Coordinates	11S 546871 E 3714845 N	SRM cover type	Chamise chaparral	**Total fuel load**	**9.97**
Land owner	San Bernardino National Forest	Pre-treatment cover type	Redshank chamise	Downed Woody Fuels	
Treatment type	Mastication	Pre-treatment height	6 feet	1 hr	0.88
Treatment name, year	Highway 74 East, spring 2007	Live woody height	4 feet	10 hr	1.53
Years since treatment	5 years	Treatment debris cover	35%	100 hour	2.10
Age at time of treatment	33 years	Live woody cover	17%	1000 hour	0.00
Elevation:	4321 feet	Herbaceous cover	16%	Live woody fuels	5.06
Slope	10 degrees	Exotic cover	12%	Herbaceous live fuels	0.00
Aspect	Flat	Native cover	21%	Dead herbaceous & litter fuels	0.40

SITE SPECIES	
Shrubs	*Adenostoma fasciculatum, Adenostoma sparsifolium, Ceanothus greggii, Opuntia polycantha, Quercus cornelius-mulleri*
Subshrubs	*Encelia actoni, Eriogonum fasciculatum, Gutierrezia microcephala, Sphaeralcea ambigua, Yucca shidigera, Yucca whipplei*
Perennials / Suffrutescents	*Achnatherum speciosum, Aristida purpurea, Datura wrightii, Elymus elymoides, Melica imperfecta, Muhlenbergia rigens, Pallaea mucronata*
Annuals	*Eriogonum gracile, Filago californica, Vulpia octoflora*
Exotics	*Avena barbata, Brassica nigra, Bromus madritensis, Bromus tectorum, Erodium cicutarium,*

Example 2. Three year old mastication treatment in manzanita dominated chamise.

SITE INFORMATION		**SITE COVER AND HEIGHT**		**SITE FUEL LOAD**	(tons/acre)
State	California				
Coordinates	11 S 545030 E 3631538 N	SRM cover type	Scrub oak mixed chaparral	**Total fuel load**	**17.42**
Land owner	Cleveland National Forest	Pre-treatment cover type	Manzanita	Downed Woody Fuels	
Treatment type	Mastication	Pre-treatment height	9 feet	1 hr	1.74
Treatment name, year	Pine Valley, spring 2008	Live woody height	4 feet	10 hr	4.06
Years since treatment	3 years	Treatment debris cover	66%	100 hour	1.80
Age at time of treatment	39 years	Live woody cover	12%	1000 hour	0.00
Elevation:	3865 feet	Herbaceous cover	4%	Live woody fuels	9.55
Slope	5 degrees	Exotic cover	1%	Herbaceous live fuels	0.10
Aspect	West	Native cover	15%	Dead herbaceous & litter fuels	0.17

SITE SPECIES	
Shrubs	*Adenostoma fasciculatum, Adenostoma sparsifolia, Arctostaphylos glauca, Ceanothus greggii, Ceanothus leucodermis, Cercocarpus betuloides, Quercus agrifolia, Quercus berberidifolia*
Subshrubs	*Eriogonum fasciculatum, Rhus trilobata*
Perennials / Suffrutescents	*Astragalus douglasii, Galium andrewsii, Gnaphalium canescens, Lonicera interrupta, Paeonia californica, Penstemon spectabilis, Phacelia ramosissim*
Annuals	*Calandria ciliata, Camissonia hirtella, Claytonia perfoliata, cordylanthus rigidus, Cryptantha intermedia, Eriogonum baileyi, Oxytheca trilobata, Stephanomeria exigua, Stephanomeria virgata*
Exotics	*Bromus tectorum, Erodium cicutarium, Lactuca serriola, Sisymbrium altissimum*

Example 3. Two year old mastication treatment in lower montane mixed chaparral.

SITE INFORMATION		SITE COVER AND HEIGHT		SITE FUEL LOAD	(tons/acre)
State	California				
Coordinates	11 S 378290 E 3829202 N	SRM cover type	Scrub oak mixed chaparral	**Total fuel load**	**27.17**
Land owner	Angeles National Forest	Pre-treatment cover type	Lower montane mix	Downed Woody Fuels	
Treatment type	Mastication	Pre-treatment height	5 feet	1 hr	2.47
Treatment name, year	Leona Divide, fall 2009	Live woody height	4 feet	10 hr	6.73
Years since treatment	2 years	Treatment debris cover	57%	100 hour	2.23
Age at time of treatment	43 years	Live woody cover	15%	1000 hour	0.00
Elevation:	4337 feet	Herbaceous cover	11%	Live woody fuels	15.49
Slope	25 degrees	Exotic cover	3%	Herbaceous live fuels	0.16
Aspect	South west	Native cover	23%	Dead herbaceous & litter fuels	0.09

SITE SPECIES	
Shrubs	*Adenostoma fasciculatum, Arctostaphylos glandulosa, Arctostaphylos glauca, Artemisia tridentata, Ceanothus greggii, Quercus berberidifolia*
Subshrubs	*Eriogonum fasciculatum, Keckiella ternata*
Perennials / Suffrutescents	*Cirsium occidentale, Eriastrum densifolium, Galium andrewsii, Lonicera interrupta, Malacothrix saxatilis, Marah macrocarpa, Penstemon grinnellii, Phacelia ramosissima, Tauchsia arguta*
Annuals	*Calandria ciliata, Camissonia hirtella, Claytonia perfoliata, Cryptantha micrantha, Cryptantha muricata, Descurainia pinnata, Emmenanthe penduliflora, Lotus strigosus, Mentzelia congesta, Phacelia brachyloba, Rafinesquia californica, Salvia columbariae,*
Exotics	*Bromus diandrus, Bromus madritensis, Bromus tectorum, Chenopodium album, Erodium cicutarium, Lactuca serriola, Senecio vulgaris, Sisymbrium altissimum, Vulpia myuros*

Management Implications and Future Work Needed

While 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 behavior 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), while at the same time 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 smoldering can also complicate fire behavior leading to fire control issues (Knapp et al., 2011; Kreye et al., 2014) and emission problems due to increased smoldering consumption (Reinhardt et al., 1997; Ottmar, 2014).

In addition, alterations in the fuel structure of chaparral from a 2-3 m high homogenous shrub canopy to a densely compacted fuel bed near the surface increases solar radiation input and surface winds, which in turn decreases fuel moistures (Agee and Skinner, 2005; Kreye et al., 2014). Recent studies have identified reduced fuel moisture as a primary driver of increased flame length, rate of spread, and fireline intensity (Knapp et al., 2011; Kreye et al., 2011, 2013a; Brewer et al., 2013) in masticated fuels. Climatic variables specific to southern California, including hot, dry summers and Santa Ana wind events, exacerbate decreased fuel moistures and are likely to intensify fire behaviors in masticated treatments. Prolonged drought periods in this region will also play a role in the effectiveness of these treatments over time.

A further complication of the widespread use of mechanical treatments is the increase of both native and non-native herbaceous fuels in these treatments, which cure and persist during the hottest and driest times of the year. Herbaceous fuels, and especially annual grasses, have flammable fuel characteristics that increase the probability of fire ignition (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, in press).

Increased use of mechanical treatments in chaparral, especially at the wildland-urban interface, warrants the need for more intensive research to better understand fire behavior in these altered fuels. Consequences of not understanding the effects of these 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 behavior are needed to create and validate masticated fuel models that can accurately predict fire behavior in these complicated fuel structures. Managers, in turn, could then integrate this information into fuel management decisions.

Literature Cited

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

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 fire regimes. *BioScience* **54**, 667-688.

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 andManagement* **236**, 18–29. doi:10.1016/J.FORECO.2006.06.002

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: Conference Proceedings.' (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 341-350. (Fort Collins, CO)

Kane JM (2007) Fuel loading and vegetation response to mechanical mastication fuels treatments. MS Thesis, Humboldt State University, Arcata, CA.

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

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, Zedler PH (2009) Large, high intensity fire events in southern California shrublands: debunking the fine-grained age-patch model. *Ecological Applications* 19, 69-94.

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

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.

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 (2013a) Effects of fuel load and moisture content on fire behaviour and heating in masticated litter-dominated fuels. *International Journal of Wildland Fire* **22**, 440–445.

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

Maxwell WG, Ward FR (1980) Photo series for quantifying natural forest residues in common vegetation types of the Pacific Northwest. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-GTR-105. (Portland, OR)

Miller C (2007) Wildfire underwriting in California: an industry perspective. *Advances in the Economics of Environmental Resources* **6**, 121-125.

NIFC (2013) Wildland fire statistics. In 'U.S. Department of the Interior, Bureau of Land Management.' (Boise, ID)

Ottmar RD (2014) Wildland fire emissions, carbon, and climate: modeling fuel consumption. *Forest Ecology and Management* **317**, 41-50.

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.

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)

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, Final Report. (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

Roby GA, Green LR (1976) Mechanical methods of chaparral modification. USDA Forest Service, Agriculture Handbook. no. 487.

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

Syphard AD, Keeley JE. Location, timing, and extent of wildfire vary by cause of ignition. *International Journal of Wildland Fire,* in press.

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.

Deliverables

Proposed	*Delivered*	*Status*
Reports:	2011 JFSP Principal Investigator Project Progress Report	**Submitted**
	2012 JFSP Principal Investigator Project Progress Report	**Submitted**
	2013 JFSP Principal Investigator Project Progress Report	**Submitted**
	2014 JFSP Principal Investigator Project Final Report	**Submitted**
Publications:	Brennan, T.J., J.E. Keeley, and D.R. Weise. Effect of mastication and other mechanical treatments on fuel structure in chaparral. *International Journal of Wildland Fire*. In review.	**In Review**
	Keeley, J.E., T.J. Brennan, and D.R. Weise. Plant community response to mastication treatments in chaparral. *Plant Ecology*. In preparation.	**In Preparation**
Workshops:	Roundtable discussion with fire, fuels and resource management staff of the Cleveland National Forest to discuss research needs and study objectives. March 10th, 2011, Rancho Bernardo Supervisors Office, Rancho Bernardo, CA.	**Completed**
	Roundtable discussion with fire, fuels and resource management staff of the Los Padres National Forest to discuss research needs and study objectives. March 16th, 2011, Casitas Fire Station, Santa Barbara County, CA.	**Completed**
	Roundtable discussion with fire, fuels and resource management staff of the Angeles National Forest to discuss research needs and study objectives. March 24th, 2011, Los Angeles River Ranger District Office, Los Angeles County, CA.	**Completed**
	Roundtable discussion with fire, fuels and resource management staff of the San Bernardino National Forest to discuss research needs and study objectives. March 23th, 2011, Mill Creek Ranger Station, San Bernardino County, CA.	**Completed**
	Discussion of preliminary results with individual fuels and resource management staff from each forest at the Chaparral Restoration Workshop in Arcadia, CA; June 2013	**Completed**
Presentations:	Brennan, T.J. *Effectiveness and effects of mastication fuel treatments in non-forested vegetation of southern California,* presented at the Annual Meeting of the California, presented at the Annual Meeting of the Association for Fire Ecology, Portland OR; December 2012.	**Presented**
	Keeley, J.E. *The Need for Chaparral Restoration: How Did We Get Here?* USFS Restoration Workshop, Arcadia, 17-19 June 2013	**Presented**

	Keeley, J.E. *Fire Hazard Reduction and Resource Protection on Chaparral Landscapes, Invited speaker,* California Board of Forestry Workshop, 8 August 2013	**Presented**
	Keeley, J.E. *Risk and the Suburbs: Historical and Political Ecologies of Fire,* Symposium on Fire and Politics, American Society for Environmental History, San Francisco, 13 March 2014	**Presented**
	Brennan, T.J. *Effect of mastication and other mechanical treatments on fuel structure in chaparral,* to be presented at the international Medecos Conference in Olmue, Chile; 7 October 2014.	**To be presented**
Outreach:	USGS film "Living With Fire." Southern California Wildfire Risk Scenario Project. 2013 (http://gallery.usgs.gov/videos/620)	**Completed**
	Mailing list of managers for sending publications, publication briefs, and website update information.	**Completed**
	Southern CA Fuel Treatments Data Set for GIS and Google Earth. Soon to be available at the **California Fire Science Consortium** website (www.cafiresci.org).	**In Preparation**
	Digital masticated fuel photo series for southern CA forests. Soon to be available at the **California Fire Science Consortium** website (www.cafiresci.org). Intentions to incorporate photos into the National Digital Photo Series website (http://depts.washington.edu/nwfire/dps/).	**In Preparation**
	GIS Database of study site locations and fuel loading data. Soon to be available at the **California Fire Science Consortium** website (www.cafiresci.org).	**In Preparation**
Website:	A project specific website was not created. Instead we have decided to incorporate all of our study findings on the **California Fire Science Consortium** website (www.cafiresci.org).	**In Preparation**
Publication Briefs for Resource Managers:	**Waiting for review and publication of manuscripts.**	**Pending**

Photos

Mastication in chaparral on the Los Padres National Forest.

**Drum cu
tting attachment on a masticator.**

Fuel photo series photo taken of the Corte Madera mastication treatment on the Cleveland National Forest.

Leona Divide crushing treatment on the Angeles National Forest.

Field crew 2011 from left to right; Chelsea Morgan, Graydon Dill, Richard Mansfield, and Callen Huff.

Field crew 2012 from left to right; Callen Huff, Chelsea Morgan, Warren Reed, and Anthony Baniaga.