# LONG-TERM FUEL AND VEGETATION RESPONSES TO MECHANICAL MASTICATION IN NORTHERN CALIFORNIA AND SOUTHERN OREGON

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## ABSTRACT

Historical land use and changes in climate have altered fire behavior and severity in fire-prone ecosystems of western North America. A variety of fuels treatments are used to abate fire hazard, restore ecosystem processes, and increase forest resilience. Mechanical fuels treatments are increasingly used to alter forest structure and fuel continuity due to impediments to the use of prescribed fire. An increasingly common fuels treatment is mechanical mastication. Mastication does not remove fuels, but instead rearranges live and dead vertical woody fuels into a compacted layer on the forest floor. While mastication reduces potential fire intensity, these compacted fuels are flammable and capable of causing tree mortality and other negative ecological consequences when they burn in prescribed fires or wildfires. A current knowledge gap is quantitative information about the rate at which masticated fuels decompose and the rate at which vegetation reestablishes within sites previously masticated. Using 25 sites across northern California and southern Oregon, this thesis examines how masticated fuels change over time. Results from this study demonstrate that the majority of mass lost from masticated fuel beds occurred in the 1 and 10-hour woody fuel classes. Because surface fire behavior is driven by these fine fuels, these findings are valuable to the planning and retreatment of masticated fuels treatments and the corresponding fire suppression efforts in masticated sites. In combination with masticated wood surface fuels, shrubs and small trees play an important role in fire behavior, acting as ladder fuels that exacerbate surface fire behavior and threaten to ignite residual trees. A lack of understanding of how woody vegetation recovers following masticated fuel treatments gives rise to questions and challenges regarding treatment longevity. In this study, species with the ability to resprout tended to recover more quickly than obligate seeding species. Residual conifer saplings or trees that establish in masticated fuelbeds also recovered rapidly, reducing the efficacy of fuels treatments. Future implementation of masticated fuels treatments should consider both woody fuel decomposition and the corresponding recovery of shrubs and small trees to maximize treatment longevity.

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# CHAPTER 1. INTRODUCTION

## 1.1 Fire and Fuels Treatments

Fire size, frequency, and severity have been increasing in western United States forests, woodlands, and grasslands (Westerling et al. 2006, Miller et al. 2009). In parallel, federal wildfire suppression costs have risen to unprecedented expenditures (Calkin et al. 2005). Shifts of fire regimes in dry forests outside the range of historic variability pose a threat to the integrity of these ecosystems (Fulé et al. 2014). Forest structure and fire behavior have been altered by an extended period of fire suppression that has caused an increase in the accumulation of dead surface fuels as well as the establishment of shrubs and small trees that dominate the midstory and function as ladder fuels (Parsons and DeBendetti 1979, Taylor and Skinner 2003, Taylor et al. 2014). Consequently, the social, ecological, and economic challenges associated with wildfires have prompted the use of fuel treatments that aim to diminish fire severity.

In an attempt to address increasing fire hazards, fuels treatments are generally executed with the broad goals of decreasing surface and crown fire hazards (Agee and Skinner 2005). Surface fireline intensity is diminished by altering surface fuels and raising crown base heights, which reduce the probability of crown fire ignition. Canopy fire spread is prevented by reducing canopy bulk densities via various forms of thinning. Lastly, in combination with aforementioned methods, the retention of large fire-resistant trees can increase forest resilience (Agee and Skinner 2005). Forest managers rely on a variety of options to meet these objectives, including chemical, burning, and mechanical treatments (Brose and Wade 2002, Agee and Skinner 2005, Knapp et al. 2011).

Among mechanical fuels treatments, mechanical mastication has become an increasingly common treatment in many fire-prone forests and woodlands (Kreye et al. 2014). Mastication utilizes large rotating cutting heads attached to tracked or wheeled machinery capable of shredding and chipping live and dead trees, shrubs, snags, and logs (Vitorelo et al. 2009). Generally, mastication treatments are implemented to alter the structure of non-merchantable shrubs and trees, which typically act as ladder fuels and are commonly found in fire-excluded forests. The use of mastication as a fuels treatment has certain advantages in that large areas of forests adjacent to communities can be treated efficiently, without substantial operational restrictions and with minimal impacts on the environment.

An important caveat of mastication is that ladder fuels are not removed, but rather rearranged and left on site in a dense compacted layer on the forest floor (Kane et al. 2009). This mulched or chipped layer may have positive impacts in the form of reducing post-treatment erosion (Hatchett et al. 2006, Harrison et al. 2016) or via acting as a mulch that stalls recovery of tree and shrub ladder fuels (Kane et al. 2010). It is important to note, however, that mastication results in greatly increased surface fuel loads of chipped and shredded material that represent novel fuelbeds (Kane et al. 2009). Masticated surface woody fuel loads are by their nature greater than pretreatment stands that were initially in need of fuel treatments, but the alteration of the arrangement results in diminished surface fire intensity (Kreye et al. 2014).

In studies of masticated fuel treatments conducted in the western United States, past research has found substantial variability and often heavy post-treatment surface fuel loading (Hood and Wu 2006, Kane et al. 2009, Reiner et al. 2009, Battaglia et al. 2010, Brennan and Keeley 2015). These substantial (i.e. 15.4 to 63.4 Mg $ha^{-1}$) levels of fuel loading have led to concerns about post mastication fire behavior and effects (Kreye et al. 2014). For example, one study following a wildfire that burned through masticated fuel treatments reported close to complete overstory tree mortality within treatment areas under moderate early fire season conditions (Safford 2008). Additionally, observations in California of prescribed fires six months after mastication have shown that when compared to controls, masticated fuels produced greater flame lengths and heat release which led to increased mortality of pole-sized oaks and conifers, conflicting with more broad management objectives (Bradley et al. 2006). In another study on prescribed fire behavior in treated fuels two and three years following mastication, fires tended to have slower rates of spread and greater flame lengths than standard fuel model projections (Knapp et al. 2011), leaving managers with concerns about predicting fire behavior and corresponding effects in masticated fuels.

Challenges associated with increased and unconventional arrangements of surface fuel loading persist in the planning, maintenance and management of masticated fuels treatments stemming from gaps in the literature, which lead to a lack of knowledge regarding treatment longevity and effectiveness (Kane et al. 2010, Kreye et al. 2014). The dominant questions addressed in this thesis aim to contribute knowledge toward a better understanding of masticated fuels treatments. These primary questions are organized into two chapters. Chapter 2 investigates the question of how long masticated fuels remain on site following treatment. Within Chapter 2, detailed investigations are presented on how fuels are distributed by size class, how specific gravity (a measure of fuel particle density), loads (i.e. mass), and height of downed fuels changes over time. Chapter 3 examines how woody vegetation responds to masticated fuels treatments. Specifically, Chapter 3 compares species with and without the ability to resprout, species richness, overstory shading, precipitation gradients and fuel loading effects on recovering vegetation.

Results from this thesis will aid fire scientists and managers in their understanding of the effect of time since treatment on these novel fuelbeds. The woody and shrub results will contribute to the improvement of fire behavior models as well as arm managers with a general understanding of how long increased surface fuel loads persist in masticated treatments. With this in mind, managers can more appropriately assess tradeoffs that may occur from treatment application. Mastication is implemented across a wide range of vegetation types in northern California and southern Oregon, and a better understanding of how vegetation recovers is also warranted. The focus on both masticated surface fuels and recovering live woody vegetation contributes to the understanding of two co-important elements regarding the dynamics within these commonly implemented fuels treatments.

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# CHAPTER 2. LONG-TERM CHANGES IN MASTICATED WOODY FUELBEDS IN NORTHERN CALIFORNIA AND SOUTHERN OREGON

## 2.1 Abstract

The use of fuels treatments is increasing as a management strategy to abate fire hazards across fire-prone ecosystems in North America. One common fuels treatment is mechanical mastication, which crushes and shreds midstory trees and shrubs into a compacted layer of woody surface fuel. Increased loading and irregular arrangements of surface fuels as result of mastication may contribute to a fire management challenge, posing risks to residual trees and causing uncertain fire behavior. Two major questions facing fuels managers are: 1) how long do masticated fuels persist and 2) how do woody fuelbeds change over time? To evaluate changes in fuels over time, I measured surface fuel loading at 25 masticated sites with a diverse range of stand characteristics and times since treatment (1 to 16 years) in northern California and southern Oregon. At seven of the 25 sites, I capitalized on the opportunity to revisit previously sampled fuels treatments to investigate and compare how surface fuelbeds transition over time. Surface woody fuel loading varied across sites and ranged from 12.1 to 91.9 Mg $ha^{-1}$ and decreased with time since treatment by an average of 2.4 Mg $ha^{-1}$ per year. Across all sites, 62% of fuels were concentrated in the 1- and 10-hour classes. In sites where previously measured data exist, 1- and 10-hour woody fuels averaged 69% and 33% reductions in mass by decomposition after 8 to 9 years, respectively, and averaged a 20% reduction of total masticated woody fuel mass. Future mastication treatments may benefit from the results by altering operational and mechanical aspects that lead to greater proportions of smaller diameter fuels, which may accelerate the rate of decomposition of surface fuel loads. Alternatively, executing prescribed burns under

conditions that mitigate risk to residual trees remains a supplemental option to reduce heavy and lingering masticated fuel loads and potentially restore ecosystem structure.

**2.2 Introduction**

The management of fire-prone landscapes has dramatic ecological, economic, and social consequences. Past land-use practices coupled with increased regional warming have increased the size, frequency, and duration of wildfires on wildlands across the western United States (Brown et al. 2004, Agee and Skinner 2005, Westerling et al. 2006), highlighting the need for effective fuels management and ecological restoration. An increasing human population living within the wildland-urban interface further complicates challenges to wildfire management, posing threats to property and human safety (Radeloff et al. 2005), altering ignition patterns and fuel connectivity (Syphard et al. 2007), and restricting the use of prescribed fire where otherwise opportune as a management tool (Quinn-Davidson and Varner 2012).

Free from the restrictions associated with burning, an increasingly common alternative fuels treatment is mechanical mastication (Figure 2.1). Mastication targets shrubland and forest midstory fuels, potentially reducing surface fireline intensity, decreasing the probability of crown ignition, and enabling fire suppression efforts (Kreye et al. 2014). Mastication converts and rearranges live woody fuels into a shredded layer of dead material on the surface of the forest floor. The resulting fuelbeds are dense and compacted accumulations of fractured woody fuels (Hood and Wu 2006, Kane et al. 2009). Mastication can be implemented following other forest thinning methods or prior to prescribed fire treatments (Kane et al. 2010, Kreye et al. 2014). In spite of the high treatment costs (up to US$ 3,459 hectare$^{-1}$, Vitorelo et al. 2009), there has been a widespread adoption of mastication in western North American shrublands and forests.

The common reliance on mastication has spawned substantial interest in the resulting fuelbeds and the consequent fire behavior and effects that may result. A study in Colorado found that masticated surface fuel loading can range from 3.2 to 8.5 times higher following treatment compared to adjacent untreated stands (Battaglia et al. 2010). Post-mastication, fire behavior in these novel fuels has been observed to be highly variable, difficult to predict, and the potential for residual tree mortality may be high (Bradley et al. 2006, Knapp et al. 2011, Kreye et al. 2014). Soil heating when masticated fuels are burned can reach lethal temperatures, injuring tree roots, particularly when soils are dry (Busse et al. 2005), as would be expected under extreme wildfire weather conditions. These changes in fire behavior and effects are attributed to increased loads of surface fuels and their compacted arrangement, creating questions and challenges for forest and fuels managers.

In parallel with these complexities, the persistence of the resulting increased surface fuel loads and the effectiveness of masticated fuels treatments remain poorly understood. Quantifying how long masticated fuels remain and how the physical composition of fuels change over time will aid in the adaptive management of fire-prone landscapes. To assess changes in masticated fuels over time, I measured characteristics of downed woody fuel loads in 25 masticated fuel treatments of varying times since treatment (range = 1 to 16 years) and vegetation types across northern California and southern Oregon. Of the 25 treatments, seven previously measured sites (detailed in Kane et al. 2009) were remeasured to provide specific within-site comparisons of how fuelbed composition and loading transition over a period of eight to nine years.

To date, no study on masticated fuels treatments spanning this range of times since treatment exists, and none have included remeasurement data from individual sites. The objectives of this project were to compare metrics (surface fuel mass, surface fuel depth, particle specific gravity, and fuel particle size compositions) that provide insight into the properties that determine fuel loading and resulting fire behavior (Rothermel 1983, Kreye et al. 2014). Individual fuel particles and fuelbeds were measured with the goal of quantifying the degree of surface fuel decomposition to contribute toward the question of how long masticated fuels persist. The specific hypotheses tested in this study were:

i. Fuel loading will decrease as time-since mastication increases;
ii. 1-hour woody particles will make a up smaller percentage of total load as time-since mastication increases;
iii. Fuelbed depth will decrease as time-since mastication increases;
iv. Specific gravity of fuel particles will decrease as time-since mastication increases;

These results are relevant for predicting the effects of mastication on fire behavior as well as the longevity or persistence of masticated surface fuel loadings in the study region, and may be of use more widely across other regions where masticated fuels treatments are applied.

## 2.3 Methods

### *2.3.1 Study Sites*

In the summer of 2014, 25 masticated fuel treatments were sampled in northern California and southern Oregon (Table 2.1), a region where many vegetation types are masticated. Sites were selected from treatment maps provided by regional forest managers and ranged from 1 to 16 years since treatment. Detailed information on the year that treatments were conducted was available for 23 of the 25 sites. Therefore, two sites (DLB and EMB) that were sampled were excluded from all time-since-treatment analyses. Seven of the 25 sites measured were previously sampled 8 or 9 years prior by Kane et al. (2009) and remeasured to compare changes in fuel loading, depth, size class composition (1-, 10-, 100 and 1000-hour), and fuel particle specific gravity.

The study area spanned the landmass north to south from 42° to 37° Latitude and east to west 119° to 123° Longitude in northern California and southern Oregon. Sites were located in the Sierra Nevada, southern Cascades, North Coast Ranges, and Klamath Mountains (Figure 2.2). In general, sites are characterized by a Mediterranean climate, with cool, wet winters and hot, dry summers. Average annual precipitation across the 25 study sites ranged from 648 to 1752 mm (PRISM Climate Group 2004). Elevation across the 25 sites ranged from 237 to 2083 m above sea level. The vegetation was highly variable spanning montane chaparral ecosystems, oak woodlands, pine-dominated and mixed-conifer forests.

*2.3.2 Field data collection*

At each of the 25 sites, thirteen to fifteen plots were randomly placed off of primary transects following Kane et al. (2009). Each plot consisted of a 0.5 m × 0.5 m frame where fuel depths were measured. Total woody and litter combined, as well as duff depths were measured 10 cm from the corners of the frame and averaged by plot (Figure 2.3). All fuels (1-, 10-, 100-hour woody, litter, and duff) within the frame were collected, bagged, and transported to the lab. Because 1000-hour woody fuels are infrequent, I followed the guidelines of Kane et al. (2009) and estimated the 1000- hour woody fuels using the planar intercept method (Brown 1974) on fifteen 20 m-long (300 m per site) transects at random azimuths off the main transects.

In the lab, fuels from each plot were sorted into standard timelag diameter classes (1-hour, < 0.625 cm; 10-hour, 0.625 to 2.54 cm; 100-hour, 2.55 to 7.62 cm (Brown 1974). Due to the irregular shape of masticated material, the timelag size classes were classified using guidelines in Kane et al. (2009) who determined particle diameters using the thinnest cross section at the midpoint. All sorted fuels were oven-dried at 85° C until no further weight loss occurred (at least 72 hours) and weighed to estimate dry weight.

In addition to changes in fuel loading, woody particle specific gravity (analogous to particle density; Sackett 1980) was measured. Immediately following weighing, three masticated woody pieces from each size class (1-hour, 10-hour, and 100-hour) and plot were randomly selected and removed (n = up to 45 from a site per size class; not all plots had particles in all size classes). To estimate these particles' specific gravity, dry samples were individually weighed and recorded. After weighing, the dry samples were submerged with a needle into a small water bath placed on top of a scale. From the scale below the bath, the buoyant force was recorded in grams to calculate each particle's specific gravity (ASTM 2002). Average specific gravity was calculated using the equation:

$$\text{Specific Gravity} = \text{oven dry weight} / \text{buoyant force}$$

for each plot by size class, and then averaged over the site by size class.

*2.3.3 Data Analyses*

Total fuel loading and average loading for each fuel particle size (1-, 10-, and 100-hour woody, duff, and litter) were compared across sites (n=25) with ANOVA. When significant differences were detected, a post-hoc Tukey-Kramer HSD test was used to isolate pair-wise differences among sites. Within each site, variation was described using standard errors. To examine the relationship between surface fuel loading and fuel bed depth at the individual plot level of all sites (n=370) and within sites (n=15) linear regressions were used.

To quantify the relationship between surface fuel characteristics and the effect of time across the 23 sites, a space-for-time or chronosequence approach (Pickett 1989) was used. A simple linear regression analysis was used to determine the relationships between fuel loading and fuelbed depth to time-since-mastication. Within this analysis, site averages (n=23) were used as replicates.

To balance the assumptions associated with space-for-time studies, such as uniform conditions across time and a deterministic pathway (Pickett 1989) of fuel decomposition, remeasurement data were utilized. Fuel characteristics were previously measured in 2005 and published for seven sites in Kane et al. (2009) allowed for paired comparisons to be made to data collected in 2014. Changes in fuel particle specific gravity, fuel loading (by timelag category, as above), and fuel depth were compared among the 7 sites using one-tailed t-tests for 1-, 10- and 100-hour fuels because one direction of change (i.e. a reduction) was assumed due to decomposition. For litter and duff, a two-tailed t-test was used based on the assumption that additional inputs occurred since treatment, maintaining the possibility of detecting changes in two directions (inputs vs. losses due to decomposition). Statistical significance for all analyses was determined using $\alpha \leq 0.05$.

**2.4. Results**

*2.4.1 Extensive plot network*

Total downed woody fuel loading differed across the 25 masticated fuels treatments ($F_{24} = 11.34$; $P < 0.0001$). Site level fuel loading ranged widely from 12.1 Mg ha$^{-1}$ to 91.9 Mg ha$^{-1}$ and averaged 30.6 Mg ha$^{-1}$. Two of the 25 sites had particularly high fuel loading (88.7 and 91.9 Mg ha$^{-1}$), and were identified as different from the other 23 sites by the Tukey-Kramer HSD test.

The remaining 23 sites had lower fuel loading (12.1 to 40.3 Mg $ha^{-1}$; Table 2.2), but did not differ, perhaps due to high variability within sites.

Within the masticated woody fuel loads, different fuel classes revealed contrasting patterns of change. 1-hour and 10-hour fuels differed across sites (both $P < 0.0001$; Table 2.2). The 1-hour fuel loads varied by two orders of magnitude, ranging from 0.7 Mg $ha^{-1}$ to 26.6 Mg $ha^{-1}$, however the vast majority (19 of the 25 sites) were not statistically different from each other based on a post-hoc Tukey-Kramer HSD. The 10-hour fuels also varied widely, ranging from 5.0 to 55.9 Mg $ha^{-1}$ across the 25 sites. 100-hour fuels were somewhat less variable than the other size classes, ranging from 1.3 to 13.3 Mg $ha^{-1}$ but still differed across the study sites ($P = 0.01$). As is commonly found within masticated fuelbeds, 1000-hour fuels were somewhat rare and highly variable. 1000-hour fuels ranged from 0.1 to 21.5 Mg $ha^{-1}$ at the 25 sites. Litter and duff followed similar patterns of substantial variation across study sites. Litter ranged from 4.8 to 22.0 Mg $ha^{-1}$ while duff ranged the widest of any individual category from 1.7 to 68.3 Mg $ha^{-1}$ (Table 2.2).

Regression analysis demonstrated that total fuel loading was significantly and negatively related to time since treatment, as expected ($P < 0.03$, $R^2 = 0.22$, Figure 2.4). The negative slope suggested a global rate of fuelbed loss attributed to decomposition of 2.4 Mg $ha^{-1}$ $yr^{-1}$. Following the overall trend, time since treatment was also significantly and negatively related to 1-hour ($P= 0.01$, $R^2 = 0.26$) and 100-hour ($P< 0.05$, $R^2 = 0.17$) fuel loading while 10-hour fuel loading approached significance ($P=0.052$, $R^2 = 0.17$) (Figure 2.4). As fuel size class decreased, the linear models generally yielded better fits when compared the observed data, as shown by the $R^2$ values above. Upon examining the fuelbed size class compositions of 23 masticated sites, the proportion of 1-hour woody fuels within fuelbeds declined with time-since-mastication ($P < 0.04$, $R^2 = 0.19$; Figure 2.5).

Woody and litter fuelbed depths were measured together at all sites and averaged 7.3 cm (± 0.4 standard error) and ranged from 3.9 to 12.5 cm.  Woody and litter fuelbed depths across the 25 sites differed significantly ($P < 0.0001$).  Fuelbed depths were hypothesized to decrease as time since mastication increased.  A simple linear regression demonstrated a lack of a significant decrease in fuelbed depth in relation to time since treatment ($P = 0.19$).  The depth of duff averaged 2.3 cm (± 0.6 s.e.) and ranged from 0.3 to 4.6 cm.  Duff depth also differed significantly across sites ($P < 0.001$).  Specific gravity of fuels within each site was also hypothesized to decrease as time since treatment increased.  No timelag size class measured (1-, 10-, and 100-hour fuels) differed in specific gravity across the 23 sites ($P = 0.054$, $P = 0.50$, and $P = 0.32$, respectively).

*2.4.2 Changes in masticated fuels 2005 to 2014: Remeasured sites*

In the seven remeasured sites, total masticated woody fuel loads lost 20% of their mass over the 8 to 9 year period between sampling.  In the seven remeasured sites, 1-hour fuels decreased by an average of 7.1 Mg $ha^{-1}$ which reflects a 69% reduction over the eight to nine year period compared to previously sampled fuelbeds, and all seven sites decreased significantly (Table 2.3).  The 10-hour fuels decreased in loading by 5.7 Mg $ha^{-1}$ corresponding to a 33% reduction in the previously sampled mass after the eight to nine years between sampling periods. While the sampling detected decreases in all sites, only 10-hour loadings at the SFR and WHI sites were statistically significant (Table 2.4).  In the 100-hour size class, no differences in loading were detected between 2005 and 2014 sampling efforts (Table 2.5).  Litter loading at the seven sites increased by an average of 2.8 Mg ha$^{-1}$ with more than half of them statistically different (Table 2.6).

In contrast to results from the extensive plot network, specific gravity was markedly reduced across woody particle sizes at all seven remeasured sites (Figure 2.6). The specific gravity of 1-hour fuel particles decreased by 23% over a period of eight to nine years between sampling. Specific gravity declined significantly at all seven remeasurement sites ($t = 12.13$, $p < 0.0001$). The specific gravity of 10-hour fuel particles also decreased by 20% over the eight to nine years between measurements; again, differences were significant at all seven remeasurement sites ($t = 12.91$, $p < 0.0001$). 100-hour fuels experienced a significant average decrease of 13% in specific gravity ($t = 2.93$, $p < 0.01$), but two of the sites (APP and TAY) did not differ over the remeasurement period when examined individually.

Litter and duff dynamics in the remeasured masticated sites were less pronounced than changes in woody fuels between the 2005 and 2014 measurements. Litter loading increased significantly at four of the seven sites, with increases ranging from 96 to 524% over period between sampling. There were no changes in duff loading at any of the seven sites. Litter and woody fuelbed depths in the majority of remeasured sites were unchanged. The MFR, SFR, and STA sites, however, all experienced significant increases in fuelbed depth (Table 2.8).

## 2.5. Discussion

### *2.5.1 Site Level Fuel Loading*

In many fire-prone wildlands in the study region, persistent masticated woody surface fuels are a management concern (Knapp et al. 2011, Kreye et al. 2014). Results from this study show more variation and substantially greater masses of downed woody fuel loading (12.1 Mg ha$^{-1}$ to 92.0 Mg ha$^{-1}$) than previous studies in masticated fuelbeds. In other western coniferous forests, masticated fuel loading was found to range from 15.3 Mg ha$^{-1}$ to 63.4 Mg ha$^{-1}$ (Hood and Wu 2006, Reiner et al. 2009, Kane et al. 2009, Battaglia et al. 2010). Despite these differences, overall averages and the trend for the majority of fuel loading to be concentrated in the 1- and 10- hour fuel size classes were similar. Studies from the southeastern United States have reported much heavier woody fuel loading in masticated loblolly pine (*Pinus taeda*) stands in South Carolina, USA ranging from 189.4 Mg ha$^{-1}$ and 192.4 Mg ha$^{-1}$ (Glitzenstein et al. 2006, Stottlemyer et al. 2015). Such contrasts in mass found in these studies could be attributed differences in sampling methodology (i.e. the exclusive use of planar intercept sampling, which provides poor estimates in masticated fuels; Kane et al. 2009), the presence of extremely high loading in the 1000-hour fuel category resulting from bark beetle-killed trees, and differences in primary productivity. The results from this study are generally consistent with past findings from studies in masticated fuels that emphasize variability and heavy surface fuel loads among masticated sites as well as the relative dominance of 1- and 10-hour fuels.

*2.5.2 Downed Woody Fuel Loading Over Time*

In this study, general estimates of the reduction of masticated woody debris due to decomposition were established over longer time periods than previously studied. Comparisons between samples conducted in 2014 and those described in Kane et al. (2009) reveal that the largest reductions in downed woody fuels at masticated sites were overwhelmingly found in the 1-hour fuel size class, which averaged a 69% reduction over the sampling period and this pattern was somewhat consistent (range 57 to 82%) across all seven of the sites used in this analysis. A similar trend was observed, although to a lesser extent, in the 10-hour fuel size class where an average reduction of 33% was found. Reductions in specific gravity of masticated fuels in this study followed a similar pattern: as fuel size class decreased, greater reductions were found over the time between sampling. This trend is in contrast to what others have found in regards to the decomposition of logging slash across multiple forest types in Washington, USA where increased diameter of particles had either a positive or no effect on decomposition rates which was speculated to be driven by quicker moisture losses within smaller particles (Erickson et. al 1985). Differing observations in masticated fuelbeds may be attributed to several factors. In a laboratory study, it has been suggested that the compacted nature of masticated fuelbeds may slow the rate of moisture desorption (Kreye et. al 2012). Slower rates of moisture loss could potentially make water (a limiting factor for decomposition) more available, at least over short time scales. Masticated fuelbeds are also generally composed of smaller diameter particles. It is expected that as fuel particle size decreases, the surface area to volume ratios increases substantially (Fasth et. al 2011), setting the stage for more biotic and chemical interactions required for decomposition. The limited research on and management relevance of decomposition dynamics of masticated fuels highlight an important research need in the region and beyond (Kreye et al. 2014).

At the 23 sites with available treatment years, an overall linear decrease in fuel loading over time was observed. I estimated a loading loss rate of 2.4 Mg $ha^{-1}$ $yr^{-1}$ using a simple linear regression and space-for-time substitution approach. Using this methodology, a relatively substantial amount of variation in the relationship between fuel loading and time since treatment was left unexplained ($R^2 = 0.22$). This variation seems generally reasonable, especially considering the sample size (23 sites) and long window of time since treatment (16 years). A study conducted in southern California on masticated fuels treatments in chaparral also examined the effect of time since treatment on fuel loading using 148 sites with time since treatments that ranged zero to eight years, and yielded a similarly low $R^2$ value of 0.34 (Brennan and Keeley 2015). These relatively low proportions of variation explained may be a relic of the problems associated with space-for-time or chronosequence approaches (Johnson and Miyanishi 2008) or simply reflect the wide variation across our study regions (and those of other studies). This study is further strengthened by the combination of individually remeasured sites and the analysis of the larger plot network.

Pre-treatment vegetation has been suggested to contribute to variability of fuel loads immediately following masticated treatments (Kane et al. 2009), and undoubtedly plays a role over longer time scales as measured here. In studies on the decomposition of leaf litter, higher lignin concentrations have been associated slower rates of decomposition (Gartner and Cardon 2004) and high lignin:nitrogen ratios have been found to stall or inhibit the decomposition process over time scales of up to a year (Melillo et al. 1982). Similar patterns have been observed within conifer twigs in the Pacific Northwest (Edmonds 1987), and likely hold true for mechanisms of decomposition of masticated wood. Variation in lignin concentration of different masticated species as well as anatomical dissimilarity of lignin within individuals (often whole individuals are masticated) may play a role in the rate and variability in which masticated woody fuelbeds decompose. Long-term studies in which pre- and post-mastication treatment vegetation are well documented with an attention to lignin and nitrogen concentrations would increase our understanding of the persistence and decomposition of these novel fuelbeds.

*2.5.3 Management Implications*

Despite the significant observations of decreasing fuel loads over time, masticated woody fuels are slow to decompose and initial post treatment fuel loadings can be extremely heavy. The findings from the vast majority of the sites outlined in this study suggest that heavy surface fuel loading can linger for periods of a decade or more following treatment. Management goals of altering ladder fuel continuity to avoid crown fire initiation may be met with masticated treatments alone, but the trade-off of persisting surface fuels for extended durations may also compromise the overall goal of fuel treatments which is to increase forest resilience when experiencing a wildfire (Agee and Skinner 2005). Past model predictions have suggested that mastication treatments may lead to substantial overstory tree mortality in wildfires, compromising the endurance of treatments (Knapp et al. 2011). In addition to model predictions, a study following 10 wildfires in California yellow pine and mixed-conifer forests compared fuel treatments that incorporated the removal of surface and ladder fuels to untreated stands (Safford et al. 2012). They found that untreated stands had surface fuel loads that averaged 34.0 Mg $ha^{-1}$ compared to treated stands with 14.1 Mg $ha^{-1}$, and treated stands were overwhelmingly effective at reducing fire severity and tree mortality (Safford et al. 2012). Comparing results from this study, my findings illustrate that masticated treatments had a much wider range of fuel loads, but generally averages compare to Safford and others' untreated stands (30.6 Mg $ha^{-1}$ in this study). These similarities in fuel load, as well as the finding that fuel loads were significantly and negatively related to tree survival in treated stands experiencing a wildfire (Safford et al. 2012) may suggest a high likelihood for outcomes of undesirable tree mortality within many of these studied masticated treatments if they are subjected to a wildfire across a wide range of time since treatments. Using prescribed fire, where intensity can be controlled, offers a potential supplemental treatment where it is operational (Knapp et al. 2011).

Fire behavior studies have documented decreased flame lengths and reduced rate of spread in masticated fuels (Knapp et al. 2011, Kreye et al. 2014), which may aid management under particular circumstances. In fire-prone areas within the wildland-urban interface, where managers may be more concerned with abating risk to lives and property rather than the maintenance and restoration of forest overstories, the utility of mastication treatments may be maximized.  This could particularly be the case in WUI regions like the Lake Tahoe Basin, where emergency response times can be as short as 10 minutes (Safford et al. 2009).  This suggestion is in contrast to mastication only treatments in remote wildlands (e.g., TRN and TRO sites in this study).  The utility of these commonly implemented treatments seems to largely depend on management objectives and proximity to the WUI.

Surface fire behavior and rate of spread are largely dictated by fine fuels (Rothermel 1983).  Results from the 23 site chronosequence and the remeasurement comparisons point to the most substantial rates of decomposition of fine woody fuels over time, primarily in the 1-hour fuel size class and, to a lesser degree, the 10-hour fuels.  It is presumed that the decay of these woody fuels and the assumed compaction that transpires over time will diminish potential fire behavior in masticated fuelbeds (Kreye et al. 2012, Kreye et al. 2014).  It is important to note that some of the remeasured sites experienced substantial increases in litter and consequently fuelbed depth.    These additions of flammable surface litter could potentially negate the expected dampening effect of fine fuel decomposition and curb expected reductions of fire behavior over time.  Observations of fire behavior in masticated fuels have found rapid fire spread in fuelbeds with accumulated litter, resulting in wide flaming zones and associated crown scorching (Knapp et al. 2011, Kreye et al. 2013).  This may be especially important in sites with residual pine overstories, where substantial needle cast would be expected.  Masticated fuel treatments are not static in regards to inputs and outputs, and should be managed with this in mind.

Because heavy surface fuel loading apparently persists over long time periods within masticated sites in dry forests, future treatments may benefit from tailoring operational or mechanical aspects of mastication or using supplemental prescribed fire. The size class distribution of masticated fuels are a function of the fuels treated and operator effort (Kane et al. 2009, Vitorelo et al. 2009). Results from this study suggest that masticated fuelbeds that are proportionally comprised of more 1-hour fuels are likely to have an accelerated rate of decomposition, reducing fuel loads and alleviating wildfire risk to residual forest over the shorter term. Alternatively, a shift of focus to eliminating heavy surface fuel loads within masticated sites using supplemental prescribed fire treatments under prescriptions that mitigate risk to residual overstories (as in Knapp et al. 2011) may increase forest resilience in the long run. Altogether, as mastication continues to be utilized, future research focusing on these aspects of fuel reduction and ecosystem resilience will contribute to our understanding and adaptive management of fire-prone wildlands.

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**Table 2.1** Description of masticated study sites in northern California and southern Oregon. Identification numbers are arranged from north to south and correspond to points in Figure 2.2.

| Id # | Site Name | Time Since Treatment | Latitude | Longitude | Location | Elevation (m) | Avg. Precip (mm) |
|---|---|---|---|---|---|---|---|
| **1** | APP05 | 9 | 42°17'14.58"N | 123° 0'22.32"W | Applegate Valley, OR (BLM) | 764 | 671 |
| **2** | APP04 | 10 | 42°17'13.32"N | 122°59'3.00"W | Applegate Valley, OR (BLM) | 720 | 648 |
| **3** | BLM06 | 8 | 42°16'26.64"N | 122°59'6.60"W | Applegate Valley, OR (BLM) | 674 | 663 |
| **4** | APP01 | 13 | 42°14'26.76"N | 123° 1'0.18"W | Applegate Valley, OR (BLM) | 565 | 672 |
| **5** | APP98 | 16 | 42°13'12.12"N | 122°56'58.74"W | Applegate Valley, OR (BLM) | 816 | 665 |
| **6** | MFR | 11 | 41°22'6.06"N | 122°18'58.92"W | Shasta-Trinity National, CA Forest (USFS) | 1348 | 1105 |
| **7** | TRO | 9 | 41°10'7.20"N | 123° 0'33.48"W | Klamath National Forest, CA (USFS) | 1756 | 1598 |
| **8** | TRN | 8 | 41° 9'59.28"N | 122°59'49.62"W | Klamath National Forest, CA (USFS) | 1741 | 1598 |
| **9** | SHL | 4 | 40°51'7.74"N | 122°24'8.94"W | Shasta-Trinity National Forest, CA (USFS) | 441 | 1752 |
| **10** | SHL2 | 10 | 40°46'34.02"N | 122°20'22.50"W | Shasta-Trinity National Forest, CA (USFS) | 411 | 1669 |
| **11** | WHI | 12 | 40°38'30.78"N | 122°35'55.62"W | Whiskeytown NRA, CA (NPS) | 382 | 1390 |
| **12** | IMR | 11 | 40°38'15.42"N | 122°27'25.56"W | Redding, CA (BLM) | 237 | 1312 |
| **13** | HF07 | 7 | 40°29'30.72"N | 123° 7'4.14"W | Shasta-Trinity National Forest, CA (USFS) | 1048 | 1104 |
| **14** | HF09 | 6 | 40°28'26.70"N | 123° 9'13.08"W | Shasta-Trinity National Forest, CA (USFS) | 839 | 1146 |
| **15** | VAN | 2 | 40°25'54.72"N | 123°31'5.70"W | Six Rivers National Forest, CA (USFS) | 851 | 1588 |
| **16** | SFR | 11 | 39°33'20.52"N | 120°14'31.68"W | Tahoe National Forest, CA (USFS) | 2040 | 883 |
| **17** | ERR | 2 | 39° 9'0.54"N | 120°46'21.54"W | Tahoe National Forest, CA (USFS) | 1280 | 1468 |
| **18** | SPR11 | 3 | 39° 7'39.72"N | 120°46'44.22"W | Tahoe National Forest, CA (USFS) | 1151 | 1468 |
| **19** | EOW12 | 2 | 39° 2'33.72"N | 120°35'8.94"W | Tahoe National Forest, CA (USFS) | 1517 | 1693 |
| **20** | DLB | - | 38°59'5.46"N | 120° 6'3.24"W | Lake Tahoe Basin Management Unit, CA (USFS) | 2013 | 936 |
| **21** | EMB | - | 38°56'38.70"N | 120° 6'0.66"W | Lake Tahoe Basin Management Unit, CA (USFS) | 2083 | 990 |
| **22** | SLT13 | 1 | 38°54'26.22"N | 119°58'17.94"W | Lake Tahoe Basin Management Unit, CA (USFS) | 1951 | 815 |
| **23** | FLL07 | 7 | 38°55'13.86"N | 120° 3'2.10" W | Shasta-Trinity National Forest, CA (USFS) | 1926 | 669 |
| **24** | STA | 11 | 38° 5'18.48"N | 120°19'19.32"W | Stanislaus National Forest, CA (USFS) | 860 | 961 |
| **25** | JD09 | 6 | 37°34'0.30"N | 119°53'1.44"W | Sierra National Forest, CA | 1316 | 1057 |

**Table 2.2** Fuel loading (± standard error) at 25 masticated fuels treatments across northern California and southern Oregon, USA. Values with different letters in each column represent significant differences according to Tukey-Kramer HSD ($\alpha \leq 0.05$).

| Site | Total Woody Loading (Mg ha$^{-1}$) | 1-hour (Mg ha$^{-1}$) | 10-hour (Mg ha$^{-1}$) | 100-hour (Mg ha$^{-1}$) | 1000-hour (Mg ha$^{-1}$) | Litter (Mg ha$^{-1}$) | Duff (Mg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| **VAN** | 92.0 (11.3)$^{a}$ | 26.6 (2.6)$^{a}$ | 49.2 (7.5)$^{a}$ | 13.2 (5.2)$^{a}$ | 3.0 | 4.8 (1.1)$^{b}$ | 21.6 (1.4)$^{bcdefg}$ |
| **SHL** | 88.7 (12.8)$^{a}$ | 12.5 (2.4)$^{b}$ | 55.9 (9.6)$^{a}$ | 13.3 (2.9)$^{a}$ | 7.0 | 9.0 (1.9)$^{ab}$ | 8.5 (1.8)$^{fg}$ |
| **JD09** | 40.3 (7.1)$^{b}$ | 6.1 (1.4)$^{cd}$ | 22.5 (4.4)$^{b}$ | 5.5 (2.2)$^{a}$ | 6.2 | 13.3 (2.3)$^{ab}$ | 25.2 (4.0)$^{bcdefg}$ |
| **TRO** | 38.5 (8.6)$^{b}$ | 3.9 (0.8)$^{cde}$ | 15.5 (5.6)$^{b}$ | 3.7 (2.4)$^{a}$ | 15.4 | 8.2 (1.3)$^{b}$ | 45.2 (12.0)$^{abcde}$ |
| **EOW** | 37.4 (5.7)$^{b}$ | 6.6 (1.3)$^{c}$ | 16.2 (3.4)$^{b}$ | 4.8 (1.4)$^{a}$ | 10.0 | 10.1 (1.8)$^{ab}$ | 21.3 (3.0)$^{cdefg}$ |
| **HF07** | 34.3 (6.3)$^{b}$ | 4.9 (1.3)$^{cde}$ | 16.3 (3.8)$^{b}$ | 10.9 (3.2)$^{a}$ | 2.7 | 7.5 (0.8)$^{b}$ | 19.3 (2.8)$^{cdefg}$ |
| **SPR** | 34.3 (3.9)$^{b}$ | 3.7 (0.7)$^{cde}$ | 13.2 (2.5)$^{b}$ | 5.2 (1.6)$^{a}$ | 12.2 | 10.6 (2.1)$^{ab}$ | 46.1 (8.8)$^{abcd}$ |
| **DLB** | 34.0 (3.9)$^{b}$ | 4.8 (0.8)$^{cde}$ | 15.1 (2.5)$^{b}$ | 4.1 (1.8)$^{a}$ | 10.0 | 22.0 (7.4)$^{a}$ | 54.9 (10.3)$^{abc}$ |
| **STA** | 31.9 (6.7)$^{b}$ | 4.9 (1.2)$^{cde}$ | 19.3 (4.1)$^{b}$ | 6.6 (3.0)$^{a}$ | 1.0 | 8.2 (1.0)$^{b}$ | 21.6 (3.6)$^{bcdefg}$ |
| **SFR** | 31.6 (2.5)$^{b}$ | 1.7 (0.3)$^{cde}$ | 5.0 (1.1)$^{b}$ | 3.3 (1.8)$^{a}$ | 21.5 | 10.6 (1.4)$^{ab}$ | 13.7 (3.9)$^{defg}$ |
| **APP98** | 29.8 (5.5)$^{b}$ | 1.3 (0.4)$^{cde}$ | 9.5 (3.4)$^{b}$ | 6.0 (2.6)$^{a}$ | 13.0 | 6.1 (1.8)$^{b}$ | 3.6 (1.6)$^{fg}$ |
| **ERR** | 28.4 (3.1)$^{b}$ | 3.6 (0.9)$^{cde}$ | 10.3 (2.0)$^{b}$ | 3.8 (1.2)$^{a}$ | 11.3 | 13.4 (1.7)$^{ab}$ | 28.5 (5.6)$^{bcdefg}$ |
| **EMB** | 26.6 (3.7)$^{b}$ | 5.8 (0.9)$^{cde}$ | 14.2 (2.8)$^{b}$ | 1.3 (0.8)$^{a}$ | 5.3 | 10.0 (1.1)$^{ab}$ | 66.4 (13.2)$^{a}$ |
| **SLT13** | 25.9 (9.0)$^{b}$ | 3.8 (1.0)$^{cde}$ | 8.0 (3.0)$^{b}$ | 10.2 (5.4)$^{a}$ | 4.0 | 15.6 (6.8)$^{ab}$ | 68.3 (18.6)$^{a}$ |
| **APP05** | 25.7 (5.6)$^{b}$ | 2.2 (0.4)$^{cde}$ | 14.7 (3.4)$^{b}$ | 6.2 (2.7)$^{a}$ | 2.6 | 6.9 (1.3)$^{b}$ | 4.4 (0.8)$^{fg}$ |
| **BLM06** | 25.2 (6.1)$^{b}$ | 1.5 (0.3)$^{cde}$ | 10.0 (2.4)$^{b}$ | 5.9 (3.9)$^{a}$ | 7.8 | 6.2 (0.8)$^{b}$ | 11.6 (3.9)$^{defg}$ |
| **SHL2** | 22.4 (3.6)$^{b}$ | 2.8 (0.4)$^{cde}$ | 10.6 (2.2)$^{b}$ | 2.7 (1.5)$^{a}$ | 6.3 | 10.6 (2.4)$^{ab}$ | 3.0 (1.1)$^{g}$ |
| **APP04** | 20.0 (3.5)$^{b}$ | 1.0 (0.2)$^{de}$ | 10.0 (1.8)$^{b}$ | 6.5 (2.3)$^{a}$ | 2.5 | 6.8 (1.1)$^{b}$ | 4.3 (1.2)$^{fg}$ |
| **IMR** | 19.6 (4.1)$^{b}$ | 2.1 (0.5)$^{cde}$ | 10.1 (2.3)$^{b}$ | 5.0 (2.0)$^{a}$ | 2.4 | 5.1 (0.9)$^{b}$ | 9.1 (3.1)$^{efg}$ |
| **TRN** | 14.2 (2.0)$^{b}$ | 2.1 (0.4)$^{cde}$ | 4.9 (1.3)$^{b}$ | 1.5 (0.9)$^{a}$ | 5.7 | 6.4 (1.5)$^{b}$ | 20.3 (8.1)$^{cdefg}$ |
| **WHI** | 13.7 (2.8)$^{b}$ | 3.0 (0.7)$^{cde}$ | 8.5 (1.7)$^{b}$ | 2.0 (1.2)$^{a}$ | 0.1 | 7.2 (1.4)$^{b}$ | 6.1 (1.4)$^{fg}$ |
| **FLL07** | 13.6 (2.7)$^{b}$ | 4.2 (0.8)$^{cde}$ | 5.5 (1.3)$^{b}$ | 2.1 (1.0)$^{a}$ | 1.7 | 10.3 (1.5)$^{ab}$ | 57.6 (7.2)$^{ab}$ |
| **MFR** | 13.9 (3.3)$^{b}$ | 2.0 (0.6)$^{cde}$ | 7.5 (2.1)$^{b}$ | 3.2 (1.4)$^{a}$ | 0.4 | 13.1 (2.0)$^{ab}$ | 13.7 (2.4)$^{defg}$ |
| **HF09** | 12.6 (2.5)$^{b}$ | 1.8 (0.4)$^{cde}$ | 7.1 (1.8)$^{b}$ | 1.5 (0.6)$^{a}$ | 2.2 | 10.6 (2.7)$^{ab}$ | 41.1 (11.1)$^{abcdef}$ |
| **APP01** | 12.1 (3.6)$^{b}$ | 0.7 (0.2)$^{e}$ | 6.3 (1.8)$^{b}$ | 2.9 (2.5)$^{a}$ | 2.3 | 6.2 (2.4)$^{b}$ | 1.7 (1.5)$^{g}$ |
| **Average** | 30.6 (4.0) | 4.5 (1.0) | 14.5 (2.4) | 5.2 (0.7) | 6.3 (1.1) | 9.6 (0.5) | 24.6 (1.7) |

**Table 2.3** Mean surface 1-hour fuel loading (± standard error) changes at seven remeasured masticated fuel treatments.

| Site | 1-hr Fuel Kane et. al 2009 (Mg $ha^{-1}$) | 1-hr Fuel 2014 Sampling (Mg $ha^{-1}$) | Change (Mg $ha^{-1}$) | % Change | t Ratio | P - value | Years Between Sampling |
|---|---|---|---|---|---|---|---|
| **APP** | 12.3 (2.8) | 2.2 (0.4) | -10.1 | -82% | 3.56 | **0.0015*** | 9 |
| **IMR** | 6.2 (1.7) | 2.1 (0.5) | -4.1 | -66% | 2.29 | **0.0175*** | 9 |
| **MFR** | 4.7 (1.1) | 2.0 (0.6) | -2.7 | -57% | 2.20 | **0.0190*** | 9 |
| **SFR** | 5.2 (0.9) | 1.7 (0.3) | -3.5 | -67% | 3.53 | **0.0014*** | 9 |
| **STA** | 15.7 (1.7) | 4.8 (1.2) | -10.9 | -69% | 5.13 | **0.0001*** | 8 |
| **TAY** | 13.2 (2.9) | 3.9 (0.8) | -9.3 | -70% | 3.12 | **0.0033*** | 9 |
| **WHI** | 11.8 (2.4) | 3.0 (0.7) | -8.8 | -75% | 3.55 | **0.0013*** | 9 |
| **Average** | **7.7 (0.8)** | **2.2 (0.2)** | **-7.1** | **-69%** | | | |

**Table 2.4** Mean surface 10-hour fuel loading (± standard error) changes at seven remeasured masticated fuels treatments.

| Site | 10-hr Fuel Kane et. al 2009 (Mg ha$^{-1}$) | 10-hr Fuel 2014 Sampling (Mg ha$^{-1}$) | Change (Mg ha$^{-1}$) | % Change | t Ratio | P - value | Years Between Sampling |
|---|---|---|---|---|---|---|---|
| **APP** | 24.6 (4.9) | 14.7 (3.4) | -9.9 | -40% | 1.65 | 0.0559 | 9 |
| **IMR** | 13.8 (4.0) | 10.1 (2.3) | -3.7 | -27% | 0.80 | 0.2151 | 9 |
| **MFR** | 8.2 (2.2) | 7.5 (2.1) | -0.7 | -9% | 0.23 | 0.4109 | 9 |
| **SFR** | 11.1 (2.3) | 5.0 (1.1) | -6.1 | -55% | 2.43 | **0.0123*** | 9 |
| **STA** | 25.0 (3.3) | 19.4 (4.1) | -5.6 | -22% | 1.07 | 0.1481 | 8 |
| **TAY** | 21.7 (4.4) | 15.5 (5.6) | -6.2 | -29% | 0.87 | 0.1968 | 9 |
| **WHI** | 16.4 (2.9) | 8.5 (1.7) | -7.9 | -48% | 2.35 | **0.0139*** | 9 |
| **Average** | **13.4 (1.3)** | **9.0 (1.1)** | **-5.7** | **-33%** | | | |

**Table 2.5** Mean surface 100-hour fuel loading (± standard error) changes at seven remeasured masticated fuels treatments.

| Site | 100-hr Fuel Kane et. al 2009 (Mg ha$^{-1}$) | 100-hr Fuel 2014 Sampling (Mg ha$^{-1}$) | Change (Mg ha$^{-1}$) | % Change | t Ratio | P - value | Years Between Sampling |
|---|---|---|---|---|---|---|---|
| **APP** | 8.6 (4.8) | 6.4 (2.7) | -2.2 | -26% | 0.44 | 0.6686 | 9 |
| **IMR** | 3.6 (1.6) | 5.0 (2.0) | +1.6 | +44% | -0.56 | 0.7104 | 9 |
| **MFR** | 1.3 (2.2) | 3.2 (1.4) | +1.9 | +146% | -1.23 | 0.8839 | 9 |
| **SFR** | 6.6 (2.9) | 3.3 (1.8) | -3.3 | -50% | 0.95 | 0.1753 | 9 |
| **STA** | 4.8 (1.6) | 6.6 (3.0) | +1.8 | +38% | -0.54 | 0.7019 | 8 |
| **TAY** | 2.1 (0.8) | 3.7 (2.4) | +1.6 | +76% | -0.61 | 0.7235 | 9 |
| **WHI** | 3.5 (1.5) | 2.0 (1.2) | -1.5 | -43% | 0.79 | 0.2187 | 9 |
| **Average** | **3.4 (0.7)** | **3.3 (0.6)** | **-0.2** | **+26%** | | | |

**Table 2.6** Mean surface litter fuel loading (± standard error) changes at seven remeasured masticated fuels treatments.

| Site | Litter - Kane et. al 2009 (Mg ha$^{-1}$) | Litter - 2014 Sampling (Mg ha$^{-1}$) | Change (Mg ha$^{-1}$) | % Change | t Ratio | P - value |
|---|---|---|---|---|---|---|
| **APP** | 10.3 (2.8) | 6.9 (1.3) | -3.4 | -33% | 1.07 | 0.1473 |
| **IMR** | 2.6 (0.6) | 5.1 (0.9) | +2.5 | +96% | -2.17 | **0.0394*** |
| **MFR** | 2.1 (1.8) | 13.1 (2.0) | +11.0 | +524% | -4.95 | **0.0001*** |
| **SFR** | 5.4 (1.5) | 10.6 (1.4) | +5.2 | +96% | -2.56 | **0.0161*** |
| **STA** | 9.9 (1.0) | 8.2 (1.0) | -1.7 | -17% | 1.24 | 0.2269 |
| **TAY** | 6.2 (1.3) | 8.2 (1.3) | +2.0 | +32% | -1.08 | 0.2908 |
| **WHI** | 3.3 (0.7) | 7.2 (1.4) | +3.9 | +118% | -2.57 | **0.0179*** |
| **Average** | 5.8 (0.6) | 8.5 (0.5) | +2.8 | | | |

**Table 2.7** Mean surface duff fuel loading (± standard error) changes at seven remeasured masticated fuels treatments.

| Site | Duff - Kane et. al 2009 (Mg $ha^{-1}$) | Duff - 2014 Sampling (Mg $ha^{-1}$) | Change (Mg $ha^{-1}$) | DF | t Ratio | P - value |
|---|---|---|---|---|---|---|
| **APP** | 6.7 (3.1) | 4.4 (0.8) | -2.3 | 15.95 | 0.73 | 0.4770 |
| **IMR** | 7.5 (3.1) | 9.1 (3.1) | +1.6 | 27.99 | -0.36 | 0.7212 |
| **MFR** | 15.0 (3.7) | 13.7 (2.4) | -1.3 | 23.75 | 0.28 | 0.7827 |
| **SFR** | 5.7 (2.1) | 13.7 (3.9) | +8.0 | 21.64 | -1.80 | 0.0866 |
| **STA** | 25.9 (4.0) | 21.6 (3.6) | -4.3 | 27.77 | 0.80 | 0.4317 |
| **TAY** | 32.7 (7.3) | 45.2 (12.0) | +12.5 | 23.25 | -0.89 | 0.3831 |
| **WHI** | 7.0 (1.5) | 6.1 (1.4) | -0.9 | 27.77 | 0.42 | 0.6778 |
| **Average** | 14.4 (1.8) | 16.3 (2.3) | +1.9 | | | |

**Table 2.8** Mean woody and litter depth (± standard error) changes at seven remeasured masticated fuels treatments (cm).

| Site | Litter and Woody Depth – Kane et. al 2009 (cm) | Litter and Woody Depth - 2014 Sampling (cm) | t-ratio | P-value |
|---|---|---|---|---|
| **APP** | 6.9 (0.8) | 7.6 (0.5) | -0.7025 | 0.4892 |
| **IMR** | 4.9 (0.8) | 5.1 (0.7) | -0.1993 | 0.8435 |
| **MFR** | 3.0 (0.4) | 6.4 (0.5) | -5.7252 | **<0.0001*** |
| **SFR** | 3.1 (0.5) | 6.0 (0.6) | -3.7425 | **0.0009*** |
| **STA** | 5.2 (0.5) | 10.1 (0.6) | -6.0663 | **<0.0001*** |
| **TAY** | 5.0 (0.6) | 6.0 (0.7) | -1.0751 | 0.2915 |
| **WHI** | 5.8 (0.6) | 7.7 (0.8) | -1.9655 | 0.605 |

**Figure 2.1** Photograph of a mechanically masticated fuels treatment at the VAN site in the Six Rivers National Forest, California.

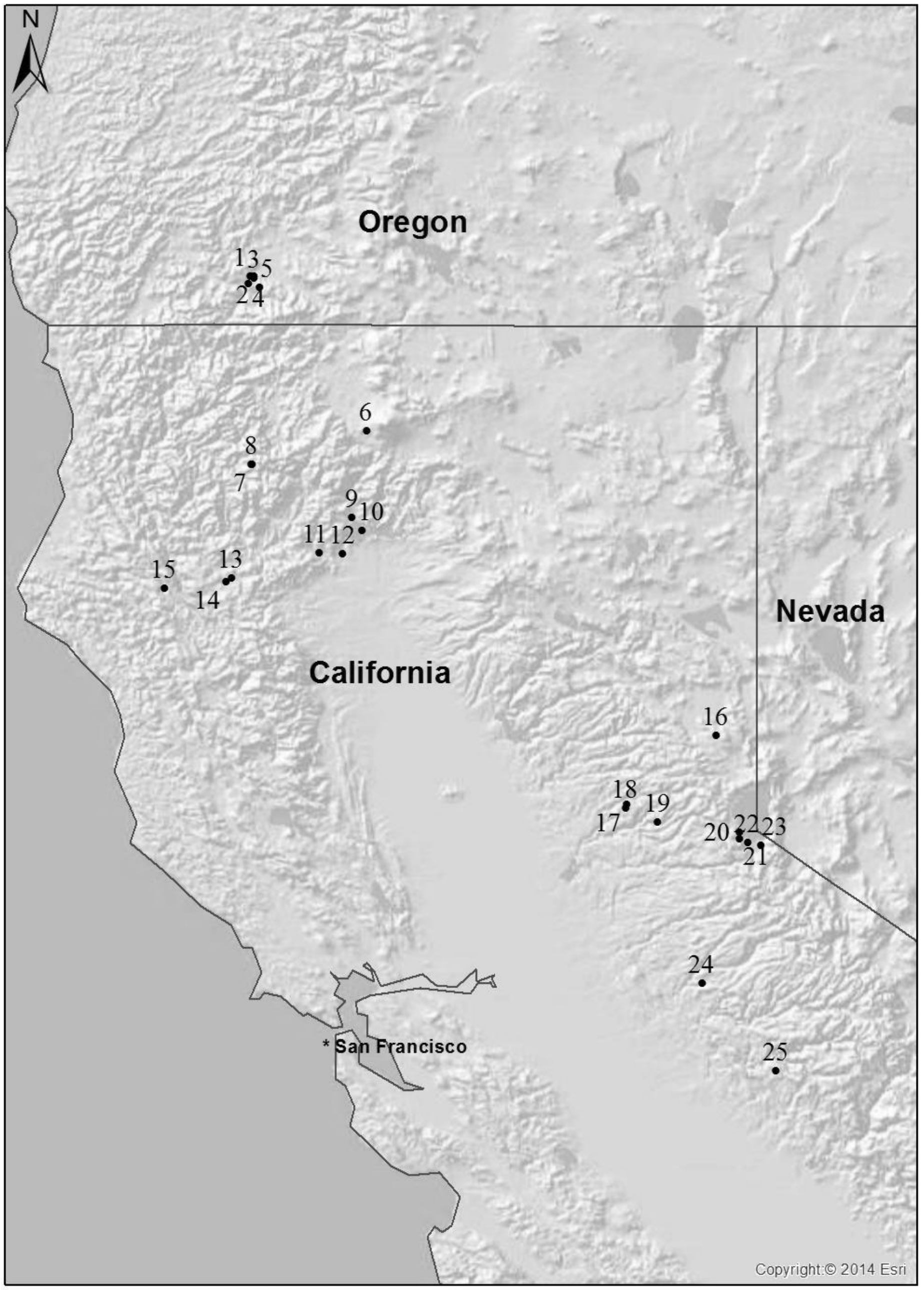
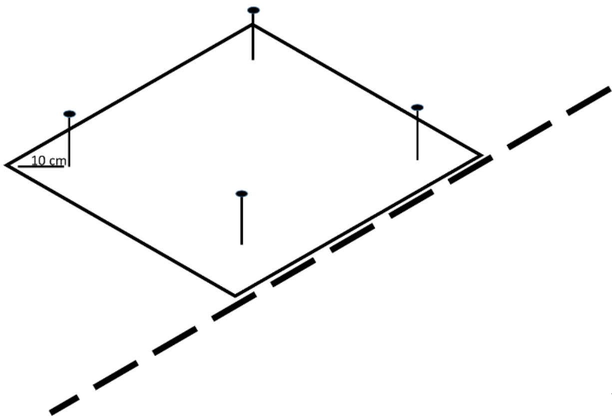



**Figure 2.2** Map of masticated study sites in northern California and southern Oregon, USA.

a.) 


b.) 

**Figure 2.3** a.) Diagram of sampling frame and metal pins. b.) Photograph of 0.5 m × 0.5 m sampling frame and pins in masticated fuels.

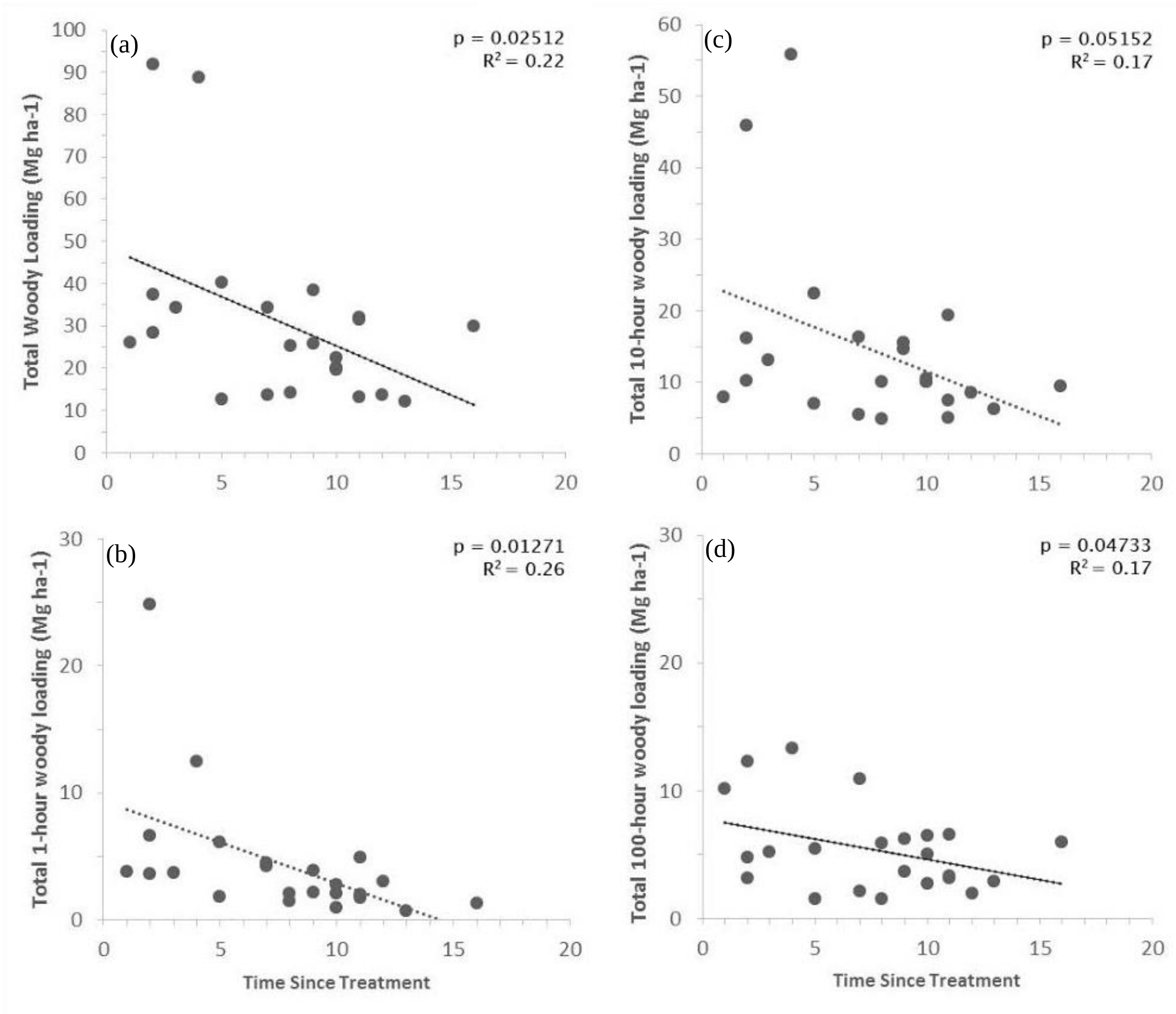



**Figure 2.4** The relationship between a.) Total woody fuel loading and time since mastication b.) Total 1-hour woody loading c.) Total 10-hour woody loading d.) Total 100-hour woody loading across 23 sampled sites in northern California and southern Oregon.

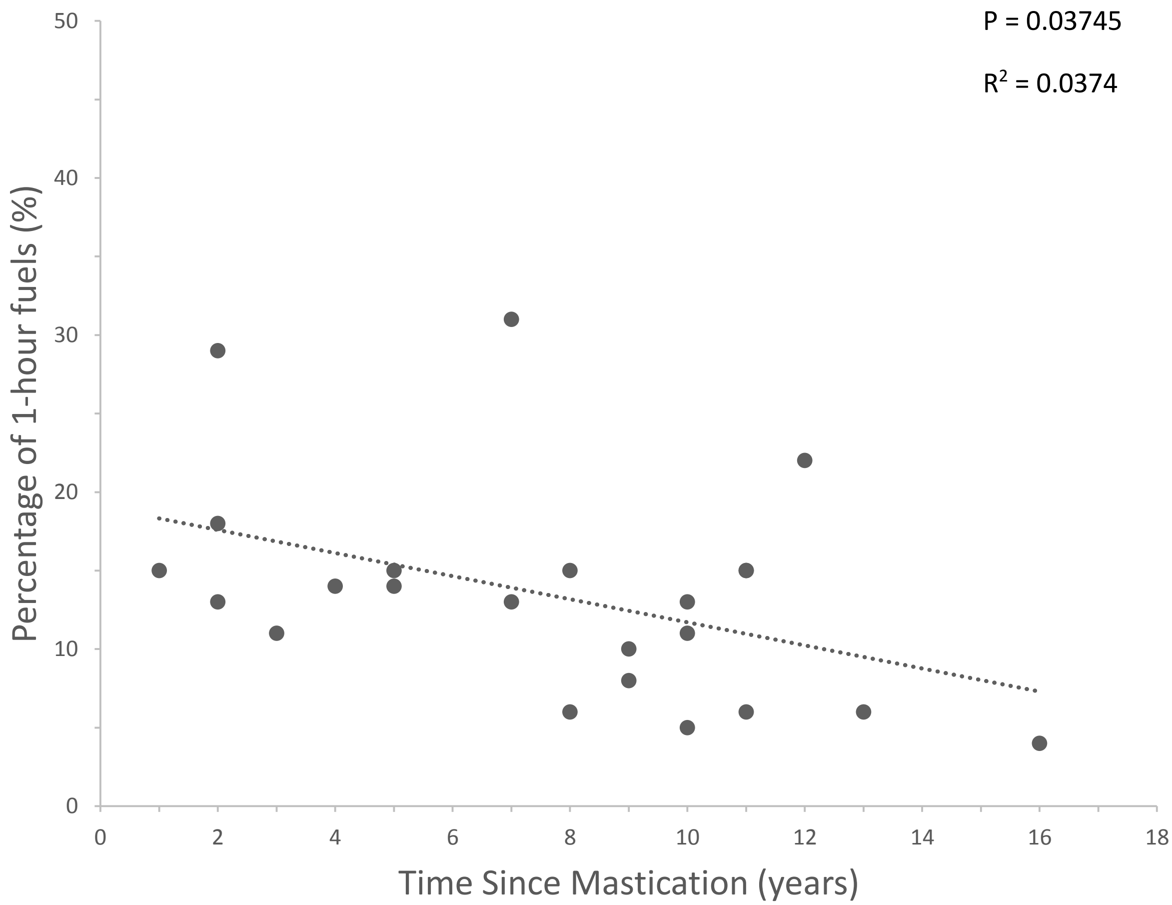



**Figure 2.5** Regression of percentage of 1-hour fuels in fuel beds and time since mastication across 23 sampled sites in northern California and southern Oregon.

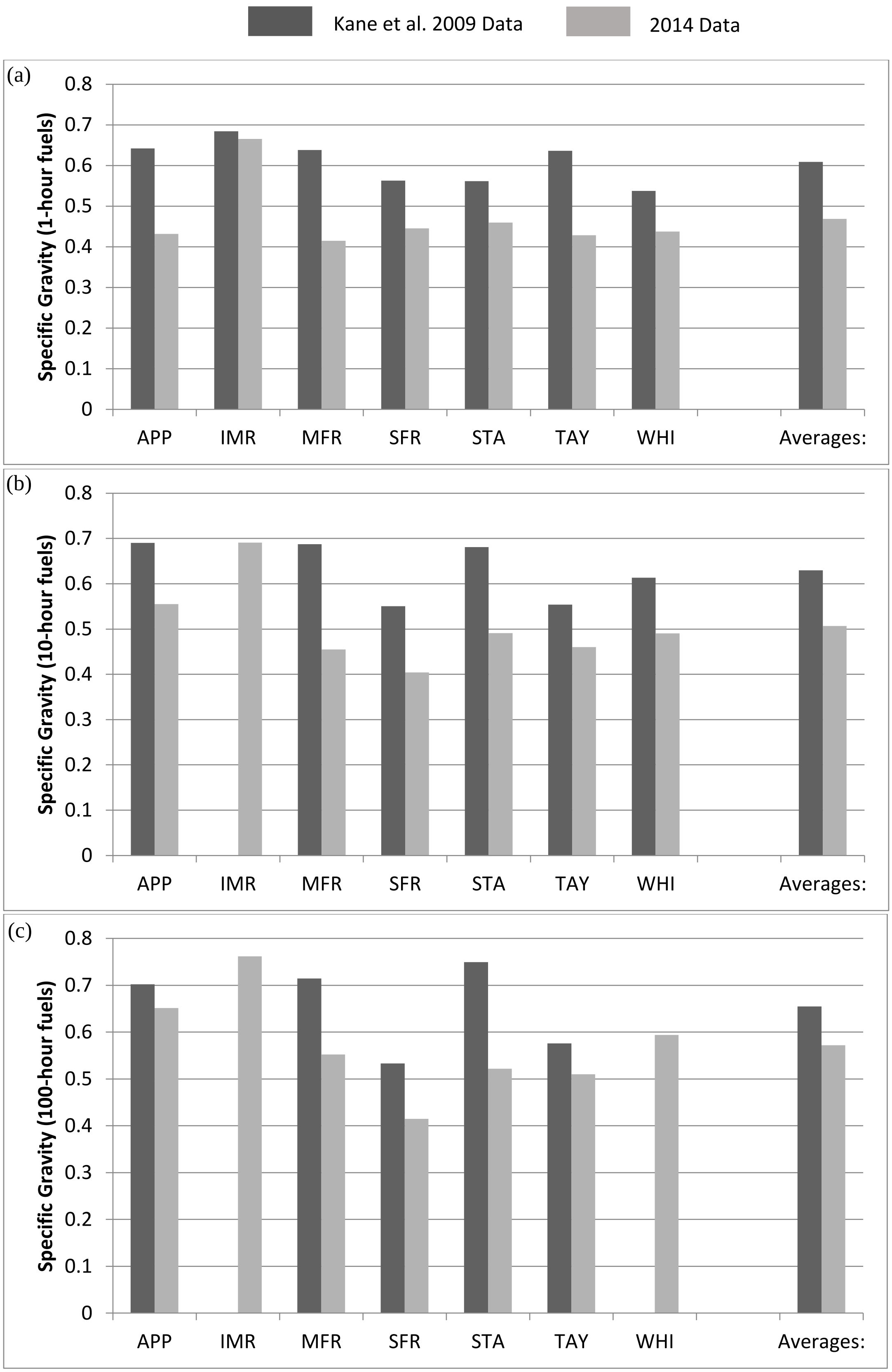



**Figure 2.6** Mean site level changes in fuel particle specific gravity a.) 1-hour b.) 10-hour c.) 100-hour masticated woody fuels. Absence of bars represents missing data.

# CHAPTER 3. LONG-TERM WOODY VEGETATION RESPONSES TO MECHANICALLY MASTICATED FUELS TREATMENTS IN NORTHERN CALIFORNIA AND SOUTHERN OREGON

## 3.1 Abstract

Fuels treatments are commonly implemented in fire-prone forests to alter stand structure in an attempt to curb potential fire behavior and effects. The use of mechanical methods, particularly mastication, is expected to increase as forest managers confront challenges associated a legacy of fire suppressed forests, an increasing human population living within the wildland urban interface and a warming climate. Masticating machinery allows forest managers to alter noncommercial forest biomass that commonly acts as ladder fuel and otherwise may remain inaccessible to other fuel treatment methods such as prescribed fire due to air quality restrictions and other environmental concerns. A current challenge presented to fuels managers is assessing treatment longevity, and of particular importance are identifying the aspects of woody vegetation characteristics that influence and the rate that woody vegetation reestablishes following mastication. To address this challenge I measured recovering woody vegetation height, cover and species composition at 25 masticated sites with a diverse range of stand characteristics and times since treatment (1 – 16 years) across northern California and southern Oregon, a region where masticated fuel treatments are common. Reestablishing vegetation was highly variable where heights ranged from 3.7 to 157.5 cm while cover ranged from <1 to 67% within treatments. Reestablishing woody vegetation height was positively related to time-since-treatment, however the additional environmental variables of average annual precipitation, canopy overstory shading and masticated fuelbed depth were found to be insignificant to the relationship of height growth. Woody vegetation with the ability to resprout tended to be taller

than nonsprouting species across all treatments and species from the genera *Quercus*, *Arctostaphylos*, and *Ceanothus* were the most abundant within these masticated sites. Vegetation recovery is linked to treatment longevity and maintenance needs. Results from this study illuminate highly variable outcomes following mastication and highlight the need for individualized site specific implementation of masticated treatments.

**3.2 Introduction**

Changes in forest structure and composition across western North America have prompted the widespread use of fuel treatments (Brown et al. 2004, Agee and Skinner 2005). Fuels treatments include a variety of mechanical, fire, and chemical methods designed to diminish fire hazard while also increasing resilience to future disturbances and stresses. Among mechanical methods, mastication has become a common fuels treatment technique. Mechanical mastication treatments chop and shred shrubs and small trees, redistributing the dead woody fuels on the surface in an attempt to alter fuel structure and decrease fireline intensity (Kreye et al. 2014). Mastication treatments have the ability to increase crown base height, reducing the risk of crown ignition and decrease canopy bulk density, which lowers the risk of crown fire spread (Kreye et al. 2014). Mechanical fuel treatments have also been shown to increase residual overstory tree vigor, potentially providing additional benefits towards the goal of increased forest resilience (Collins et al. 2014). The use of mastication as a fuels management tool will likely increase in the face of impediments to the use prescribed fire, the need for forest restoration, and an increase in area within the wildland-urban interface (Kreye et al. 2014).

Mastication is generally applied in shrubland and forested ecosystems and often targets woody midstory trees and shrubs that act as ladder fuels. Because of the relatively important roles they play as conduits for transitions from surface to crown fires and their contribution toward surface fire behavior, diminishing ladder fuels are critical aspects of fuels treatment efficacy and longevity (Agee and Skinner 2005; Kreye et al. 2014). Across the region, these shrubs also provide important ecological functions such as browse, shelter, and nesting structures for wildlife (Kauffman and Martin 1990). Mastication can be employed in combination with other mechanical thinning operations, as a precursor to prescribed fire treatments, or as a stand-alone prescription (Kane et al. 2009). Live vertical woody surface fuels are converted into dense layers of shredded material that can result in heavy downed woody fuel loads (Kane et al. 2009).

Mastication rearranges rather than removes or consumes fuels; therefore, the longevity of treatment effectiveness is dictated by both residual woody surface fuels and the regrowth of shrubs and trees. If heavy surface fuels linger following treatments and vegetation recovers rapidly, the potential to intensify wildfire hazard compared to pretreatment stands exists, particularly if there is more available combustible mass on site. It has been suggested that surface fires in masticated fuel beds under shrub vegetation may have the potential to preheat live biomass; making it available for combustion in circumstances that live fuel moisture would otherwise prohibit (Knapp et al. 2011). Alternatively, heavy masticated surface fuels may potentially function in a desirable manner from a fuel treatment maintenance perspective by suppressing the regrowth and germination of vegetation as a result of a mulching effect (Kane et al. 2010, Potts et al. 2010).

Fuels treatments are often ineffective as a one-time prescription, requiring subsequent treatments to maintain efficacy (Agee and Skinner 2005, Reinhardt et al. 2008), and presumably the same is true with mastication. The rate of woody vegetation recovery will have an effect on the functional lifespan of fuel treatments and factors such as the life history characteristics of the species masticated likely plays a role in the response to this type of mechanical disturbance.

Specifically, woody species that resprout may have a presumed advantage at persistence over those that regenerate from seed alone because of the presence of an intact root system that could respond with substantial vigor (Bond and Midgley 2001). "Seed obligates" may be further hindered from establishment by the thick mulch created by mastication that may inhibit germination and seedling growth (Kane et al. 2010). Studies in California chaparral ecosystems composed predominantly of resprouting *Adenostoma fasciculatum* following mastication have been conducted and findings suggest relatively rapid recovery of woody shrubs. For example, northern California chaparral was observed to achieve up to 48% cover in only three years following mastication (Potts et al. 2010), and southern California stands of masticated chaparral were able to recover to pretreatment mass in just five years following treatment (Brennan and Keeley 2015). Masticated fuel treatments are used widely outside of *A. fasciculatum* dominated shrublands, therefore more research across a diverse range of vegetation types is a necessity.

Despite the profusion of mastication as a fuel treatment in fire-prone wildlands of the western United States, little is known about the long-term effects on vegetation recovery within this novel disturbance. Stemming from this gap, even less is known about contributing factors such as precipitation, the effects of overstory canopy cover, and elevation within forested environments. I am aware of no study focused on longer-term time scales, and existing literature lacks information on vegetation recovery within masticated treatments with residual overstory canopies where masticated surface fuel loads are likely heavier following treatment compared to nonforested or shrubland ecosystems. To contribute towards the management and understanding of the ecological effects of mastication, the objectives of this study were to characterize, compare and assess woody vegetation recovery within 25 masticated fuel treatments spanning a wide range of times since treatment (1 to 16 years) in northern California and southern Oregon wildlands. Specifically, the hypotheses tested were:

1.) The height and cover of woody vegetation will increase with time since treatment;
2.) Species with the ability to resprout will recover more quickly than non-sprouting species;
3.) Canopy overstory shading will diminish woody vegetation recovery following mastication;
4.) Deeper fuelbeds will inhibit woody vegetation recovery following mastication; and
5.) Treatments with higher annual precipitation will recover more quickly compared to sites experiencing more dry conditions.

The results presented within this study provide insight in to the factors that contribute towards the rates of recovery of woody vegetation from mastication in northern California and southern Oregon wildlands and perhaps more widely.

## 3.3 Methods

### *3.3.1 Study Sites*

In the summer of 2014, 25 masticated fuel treatments were visited and sampled in northern California and southern Oregon (Figure 3.1). All sites were selected and assigned a treatment year based on available maps of treated areas that were provided by forest managers on federally managed property (USDA Forest Service, USDI National Park Service, and USDI Bureau of Land Management). Time since mastication at the sites ranged from 1 to 16 years. The landscape across the region is topographically complex and elevations at the sites ranged from 237 to 2083 meters above sea level. The average annual precipitation across the region spanned a gradient of 648 to 1752 mm (PRISM Climate Group 2004). The treated sites spanned several mountain ranges across the region including the Sierra Nevada, southern Cascades, North Coast Ranges, and the Klamath Mountains encompassing diverse fire-prone ecosystems (Sugihara et al. 2006) where mechanical fuel treatments, including mastication are common. Downed masticated fuel loads were estimated at the sites at the time of vegetation sampling (see Chapter 2) and ranged from 12.1 Mg $ha^{-1}$ to 92.0 Mg $ha^{-1}$ (Table 3.1). Reflecting the diversity the abiotic attributes and land-use history of the sites, the vegetation composition at the sites was varied, spanning mixed shrub and oak woodlands, ponderosa pine (*Pinus ponderosa*) and mixed conifer forests.

*3.3.2 Field Methods*

At each site, 15 circular plots with 3.0-meter radii (plot area = 28.3 $m^2$; 424.5 $m^2$ at each site) were scattered in a random sampling approach along transects within treated areas, avoiding edges. Plots were divided into four quadrants. All woody species that established following mastication in each quadrant were identified (nomenclature follows Baldwin et al. 2012) and recorded. For each species, I measured average height to the nearest cm. A modified Daubenmire cover class was assigned (1= <1%, 2= 1-10%, 3= 10-25%, 4= 25-50%, 5= 50-75%, 6= >75% cover) and recorded for each species within the four quadrants. At the center of every plot, residual overstory canopy cover was estimated in four cardinal directions from approximately 1.37 meters to using a convex densiometer and the four values were averaged per plot. To measure downed woody fuel loads of the masticated fuelbeds, a sampling frame was positioned near the center of the plot. 1-, 10-, and 100-hour woody fuels were collected in a 0.25 $m^2$ sampling frame following methods in Kane et al. (2009). 1000-hour fuels were sampled on 20-meter transects using the planar intercept method (Brown 1974).

Three primary measures of vegetation response to mastication were used: woody vegetation height; cover; and species richness. Woody vegetation heights within each plot were derived by averaging the tallest individually recorded species in each quadrant (n=4 quadrants). Cover classes of each species present were added by quadrant and averaged at the plot level of each sampling plot. Plot woody cover had the potential to be greater than 100% in the case of multiple layers of reestablishing vegetation. Woody species richness at each site was measured by recording the total number of species found in each within each treatment.

*3.3.3 Data Analyses*

Means and standard errors were calculated at the site level for woody vegetation cover using midpoints of cover classes and woody vegetation height at all sites. Average cover and height of reestablishing woody vegetation in masticated fuel treatments was compared across sites (n=25) using analysis of variance (ANOVA). When differences were detected, a post-hoc Tukey-Kramer HSD test was used to determine significance of pairwise differences among sites. Linear regression was used to evaluate the effects of time-since-treatment on the cover and height of reestablishing woody vegetation, with the time-since-treatment (years) as the independent variable and average shrub cover (cover class midpoint; %) and shrub height (cm) as the dependent variables. Using an additive modeling approach, additional variables of average annual precipitation, average overstory canopy percent openness, and average fuelbed depth were included individually as predictor variables to test for significance and examine the impact on the relationship with time since treatment.

To explore the effect of certain life history characteristics following mastication, all woody species were grouped into categories of sprouters or non-sprouters (Keeley and Zedler 1978). Classification as resprouter or nonsprouter was based on species traits outlined by the

United States Forest Service (Fire Effects Information System). At each site, the average height of resprouting and nonsprouting species was compared using two sided t-tests. Conifers were excluded from this portion of the analysis for two reasons: they may have been avoided by masticator operators (personal observations) and the primary focus was on woody shrubs and hardwood trees. Statistical significance for all analyses was determined using $\alpha \leq 0.05$.

**3.4 Results**

Average woody vegetation height at the 25 masticated sites was 64.5 cm and differed significantly across sites ($F_{24} = 16.49$; $P < 0.0001$). The average height of woody vegetation ranged from 3.7 to 157.5 cm. A post-hoc Tukey-Kramer HSD test revealed that not all pair-wise comparisons were significant, and separated the 25 sites into 9 overlapping categories (Table 3.3).

Average woody vegetation height significantly increased with time since treatment ($P < 0.05$). Time since mastication alone was capable of explaining 20% of the variance across the treatments (Figure 3.2). When the intercept is constrained to zero based on the assumption that all measured woody vegetation was masticated to the ground surface, the height growth rate suggests masticated woody vegetation recovered at an average of 8.1 cm per year across all sites. The addition of individual variables of average annual precipitation, canopy openness, and fuelbed depth all lacked a significant effect (all $P > 0.05$) in the regression when considered with time since treatment and were therefore excluded from any further analyses.

Reestablishing woody vegetation cover differed significantly across the 25 masticated fuels treatments ($F_{24} = 16.90$; $P < 0.0001$). The average cover across all sites was 27%, and ranged from <1% at the VAN site (2 years since mastication) to 67% at the SFR site (9 years since mastication). Sites on both the highest (SFR and STA) and lowest end (DLB, EMB, and VAN) of cover were different from the remaining 20 sites (based on the results of the pairwise differences with Tukey-Kramer HSD). Sites in the middle range considerably overlapped in the amount of shrub cover (Table 3.3). Reestablishing woody vegetation cover was not significantly related to time since treatment (P = 0.13; Figure 3.3). The addition of individual variables (average annual precipitation, canopy openness, and fuelbed depth) were also non-significant (all P > 0.05) when considered in the regression analysis.

Mastication resulted in a diversity of woody species across the 25 study sites. The total number of woody species found within masticated fuel treatments sampled in this study was 64 from 21 families. Species richness within the masticated sites ranged from 3 to 16 and averaged 9.3 species per site. The most commonly occurring genera within sites were *Quercus* and *Arctostaphylos*. The two most frequently occurring recovering woody species for each site are described in Table 3.2.

Resprouting species were taller than nonsprouting species of hardwood shrubs and trees at 12 out of the 25 sites (P <0.05; Table 3.3). At four of the sites, the opposite trend was observed: nonsprouters were taller than resprouting species. The remaining 7 sites revealed no significant differences between the heights of resprouting and nonsprouting shrub species. When observations were examined together across all sites, resprouting species were taller on average compared to nonsprouting species (P = 0.0001; Table 3.3), but the magnitude of the differences in height were subtle (sprouters mean = 57.2 cm; nonsprouters mean = 46.2 cm).

### 3.5 Discussion

This study of woody plant recovery following mastication illuminates a broad range of potential outcomes following treatment. Within these sites, few strong patterns emerged over the wide range of time since treatments examined and recovering vegetation responses were highly variable (Figure 3.4). These highly variable outcomes of woody vegetation response following masticated treatments are analogous to the variability observed by other studies of concomitant downed woody fuel loads of this mechanical treatment (Kreye et al. 2014).

Reestablishing woody vegetation height significantly increased with time since mastication, and a single variable (time-since-treatment) was able to account for 20 percent of the explained variance within the sites observed. The additional variables hypothesized to contributed either positive (increased precipitation) or negative (residual overstory shading and fuel bed depth) effects on growth were not significant in the relationship between height and time since mastication. This result is somewhat unsurprising considering all of the factors that can contribute towards plant growth ranging from competitive biotic interactions to abiotic local site level conditions. A study on the growth of *Arctostaphylos viscida*, a common non-sprouting shrub that frequently occurred within masticated sites of this study, also found that within site variability of stem growth was not correlated and likely masked the influence of environmental variables of elevation, aspect, slope, soil depth and soil texture (Minore et al. 1988). Additionally, a horticultural study on the effects of mulch depths that ranged from 0 to 15 cm on the height, width, basal and crown foliage growth of five arid shrub species of the southwestern United States found no effect from any treatment level on these factors (Hild and Morgan 1993). Results from this study are similar and suggest that the precipitation gradients, overstory shading characteristics, and masticated fuelbed depths found in these sites do not contribute significantly to the hindrance or benefit of the regrowth of woody shrubs and trees.

Post-mastication woody vegetation heights in this study tended to be similar to other observations in masticated and other fuel treated shrublands of California chaparral. In northern California woody shrubs grew to approximately 55 cm three years following treatments (Potts et al. 2010), and another study in southern California observed an average shrub height of 110 cm in masticated treatments that ranged from one to eight years since mastication (Brennan and Keeley 2015). Sites from this study with the tallest recovering woody vegetation (TRN, APP05, SFR, WHI, and APP98) all experienced at least eight years of time since mastication and were most frequently dominated by resprouting *Ceanothus* and *Quercus* species (Table 3.2). In a study on *Quercus douglasii* in central California, authors have suggested that these hardwood trees grew more vigorously from stump sprouts than from true seedlings following fire (McClaran and Bartolome 1989), a trait that may favor similar recruitment and dominance following mechanical mastication of treated species in this study. These results underscore the need to more fully understand resprouting in these and other fire-prone ecosystems where fire and mechanical fuels treatments are so widely employed (Keeley and Zedler 1978, Bond and Midgley 2001, Kane et al. 2010).

Flame lengths in vertical shrub fuels are tightly linked to fuel height (Rothermel 1972). The estimated average vertical growth rate of 8.1 cm per year across these fuel treatments is intended to provide fuel managers with a rough estimate towards a rate of woody vegetation recovery in masticated treatments in northern California and southern Oregon, however considerable variability around this rate exists. From a management perspective, identifying thresholds of midstory ladder fuel vegetation height to fire hazard would be beneficial in estimating treatment longevity and rough estimates of retreatment needs may be best if viewed with an adaptive management perspective. Furthermore, site specific decision making and well defined goals will remain critical to defining successful fuel treatment implementation (Brown et al. 2004) and treatment longevity.

Estimates of cover in these masticated study sites were less than observed in other studies. Fuel treatment sites dominated by *Adenostema fasiculatum* reached up to 48% cover by the third year after mastication in California (Potts et al. 2010). Masticated sites within three years of treatment examined in this study reached 34.5% cover at SPR11 where *Calocedrus decurrens* (a common conifer in the region) most frequently occurred, but overall were generally less and many remained lower over extended periods of time comparatively (Table 3.3). *C. decurrens* has been known to reestablish prolifically following high severity disturbances such as fire when a seed source is near, especially in high seed production years (Franklin et al. 2006) and dense conifer regeneration can be problematic in regards to treatment longevity (Battaglia et al. 2008). Sites with the lowest cover (0.7 to 10.1%) were generally sampled within 2 years of mastication (SLT, EOW, and VAN) and the most frequently occurring species were comprised of a mix of sprouting and nonsprouting species. Additionally, anecdotal evidence from sites on the highest end of the cover class spectrum suggested that recovering vegetation tended to be most frequently dominated by sprouting species such as *Quercus garryana*, *Quercus kelloggii*, *Ceanothus velutinus*, *Arctostaphylos patula*, *Symphoricarpos rotundifolius* and *Chamaebatia foliolosa*. Sprouting shrubs and small trees can abbreviate the period of treatment efficacy. Sites dominated by these species should be evaluated carefully to avoid reduced longevity or perhaps designed so that repeated treatments are possible (i.e. located near roads or the WUI where transportation costs are minimized).

Reestablishing woody vegetation cover was not found to significantly increase with time since mastication. The opportunistic nature of site selection in this study may have been confounded by issues commonly related to chronosequence or space for time substitutions (Johnson and Miyanishi 2008). A lack of detected significance is likely due to the potential variability of the response to mastication of these diverse woody species of shrubs and trees found in the sampled treatments, unmeasured site level environmental factors, differences in productivity across the large study area and operational differences between mechanical treatments.

Previous shorter term studies have compared masticated fuel treatments to prescribed fire, and have suggested that masticated fuelbeds may have a negative impact on vegetation regrowth (Kane et al. 2010, Potts et al. 2010) which could have potential benefits in regards to treatment longevity. Others have also highlighted evidence over longer time scales that mastication alone compared to mastication plus fire treatments recover more slowly, and that remasticated treatments may experience the most longevity in regards to time since treatment (Brennan and Keeley 2015). Although no comparisons are made in this study to other treatment combinations, fuelbed depth failed to be a significant factor in the analyses. These findings may suggest that deeper fuelbeds are not inhibiting the reestablishment of woody vegetation, at least over the time scales studied here. Low intensity prescribed fire in pine stands have been demonstrated to increase nitrogen availability (Schoch and Binkley 1986). It is possible that a pulse in nutrients released in burned masticated stands of the previously mentioned studies comparing treatment combinations contributed to faster vegetation regrowth rather than inhibition from a mulching effect where nutrients may be immobilized in slowly decomposing woody material. Identifying compound driving forces within pant community growth and recovery can be complex, and significant effects can be masked even under controlled experimental settings (Hild and Morgan 1993).

Evaluating masticated fuel treatments in regards to longevity and effectiveness, like other fuels management strategies, is multifaceted. Past research has highlighted that fuel treatment success is dependent on site specific factors and decision making that relies on well-defined management goals (Brown et al. 2004, Stephens and Moghaddas 2005, Reinhardt et al. 2008). Results from this study demonstrate significantly different responses of reestablishing woody vegetation to mastication in regards to height and cover, with implications toward variability of potential fire behavior and effects in the event of a wildfire. Additionally, observations from sites studied here seem to suggest that mastication in northern California and southern Oregon tends to favor resprouting species within the *Quercus*, *Arctostaphylos* and *Ceanothus* genera. Resprouting species have a measureable advantage for persistence following mastication. Future implementation of masticated fuel treatments aiming to maximize utility may benefit from avoiding sites dominated by resprouting shrubs and trees, selecting sites where favored species are in line with management goals, and incorporating expected ranges of variability into management plans with implications of retreatment in mind.

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**Table 3.1** Description of masticated sites in northern California and southern Oregon. Map identification numbers correspond to points in Figure 3.1.

| Time Since Mastication | Site | Map ID | Canopy Openness (%) | Fuelbed Depth (cm) | Annual Precip. (mm) |
|---|---|---|---|---|---|
| 1 | SLT13 | 22 | 58.7 | 5.3 | 815 |
| 2 | EOW | 19 | 54.1 | 7.3 | 1693 |
| 2 | ERR | 17 | 27.7 | 8.9 | 1468 |
| 2 | VAN | 15 | 73.3 | 10.9 | 1588 |
| 3 | SPR11 | 18 | 42.2 | 9.5 | 1468 |
| 4 | SHL | 9 | 78.1 | 12.5 | 1752 |
| 5 | HF09 | 14 | 56.8 | 7.1 | 1146 |
| 5 | JD09 | 25 | 37.5 | 10.4 | 1057 |
| 7 | FLL07 | 23 | 63.8 | 5.2 | 669 |
| 7 | HF07 | 13 | 40.5 | 7.2 | 1104 |
| 8 | BLM06 | 3 | 41.5 | 7.4 | 663 |
| 8 | TRN | 8 | 97.9 | 4.5 | 1598 |
| 9 | APP05 | 1 | 57.2 | 7.6 | 671 |
| 9 | TRO | 7 | 70.0 | 5.9 | 1598 |
| 10 | APP04 | 2 | 44.1 | 7.3 | 648 |
| 10 | SFR | 16 | 79.1 | 6.0 | 883 |
| 11 | SHL2 | 10 | 39.1 | 9.5 | 1669 |
| 11 | IMR | 12 | 64.8 | 5.1 | 1312 |
| 11 | MFR | 6 | 28.4 | 6.4 | 1105 |
| 11 | STA | 24 | 55.1 | 10.1 | 961 |
| 12 | WHI | 11 | 45.8 | 7.7 | 1390 |
| 13 | APP01 | 4 | 84.0 | 5.1 | 672 |
| 16 | APP98 | 5 | 62.9 | 8.3 | 665 |
| Unknown | DLB | 20 | 51.4 | 5.8 | 936 |
| Unknown | EMB | 21 | 54.1 | 5.4 | 990 |

**Table 3.2** Most frequently occurring species at each site. Columns with more than one species occurred at equal frequency.

| Site | Most Frequent species | Second Most Frequent Species |
|---|---|---|
| SLT13 | *Purshia tridentata* | *Rosa woodsii* |
| EOW | *Arctostaphylos viscida* | *Pinus ponderosa* |
| ERR | *Quercus kelloggii* | *Ceanothus integerrimus*, *Ribes roezlii* |
| VAN | *Arctostaphylos patula* | *Quercus garryana*, *Toxicodendron diversilobum* |
| SPR11 | *Calocedrus decurrens* | *Symphoricarpos mollis* |
| SHL | *Quercus garryana* | *Quercus kelloggii* |
| HF09 | *Quercus garryana* | *Ceanothus leucodermis* |
| JD09 | *Quercus chrysolepis* | *Chamaebatia foliolosa* |
| FLL07 | *Rosa woodsii* | *Purshia tridentata*, *Symphoricarpos mollis* |
| HF07 | *Arctostaphylos viscida* | *Quercus garryana* |
| BLM06 | *Toxicodendron diversilobum* | *Rosa gymnocarpa* |
| TRN | *Ceanothus velutinus* | *Arctostaphylos patula* |
| APP05 | *Quercus garryana*, *Toxicodendron diversilobum* | *Quercus kelloggii* |
| TRO | *Ceanothus velutinus* | *Arctostaphylos patula* |
| APP04 | *Toxicodendron diversilobum* | *Quercus garryana* |
| SFR | *Ceanothus velutinus* | *Symphoricarpos rotundifolius* |
| SHL2 | *Pinus sabiniana* | *Quercus garryana*, *Toxicodendron diversilobum* |
| IMR | *Arctostaphylos viscida* | *Pinus attenuata* |
| MFR | *Arctostaphylos patula* | *Ceanothus prostratus*, *Ceanothus velutinus* |
| STA | *Chamaebatia foliolosa* | *Arctostaphylos viscida* |
| WHI | *Heteromeles arbutifolia* | *Pinus attenuata* |
| APP01 | *Ceanothus cuneatus* | *Toxicodendron diversilobum* |
| APP98 | *Toxicodendron diversilobum* | *Quercus garryana* |
| DLB | *Abies concolor* | *Chrysolepis sempervirens* |
| EMB | *Abies concolor* | *Chrysolepis sempervirens*, *Quercus vaccinifolia* |

**Table 3.3** Comparisons of average recovering vegetation metrics, species richness and downed woody fuel loading (± standard error) at 25 masticated fuels treatments in northern California and southern Oregon. Values with different letters in each column represent significant differences based on Post-hoc Tukey-Kramer HSD tests.

| Site | Average Woody Height (cm) | Average % Vegetation Cover | Species Richness | Downed woody fuel loading (Mg $ha^{-1}$) |
|---|---|---|---|---|
| SLT13 | 21.1 (4.3)$^{hi}$ | 8.2 (3.3)$^{hi}$ | 6 | 25.9 (9.0) |
| EOW | 30.5 (6.6)$^{ghi}$ | 10.1 (3.5)$^{hi}$ | 12 | 37.4 (5.7) |
| ERR | 65.9 (10.9)$^{cdefgh}$ | 27.2 (5.3)$^{cdefgh}$ | 11 | 28.4 (3.1) |
| VAN | 3.7 (0.8)$^{i}$ | 0.7 (0.2)$^{i}$ | 6 | 92.0 (11.3) |
| SPR11 | 56.7 (5.7)$^{defghi}$ | 34.5 (5.2)$^{bcdefg}$ | 16 | 34.3 (3.9) |
| SHL | 106.0 (10.2)$^{abcd}$ | 49.4 (6.9)$^{abc}$ | 14 | 88.7 (12.8) |
| HF09 | 42.2 (5.4)$^{ghi}$ | 17.0 (2.6)$^{efghi}$ | 8 | 12.6 (2.5) |
| JD09 | 43.6 (9.2)$^{fghi}$ | 38.8 (7.8)$^{bcde}$ | 9 | 40.3 (7.1) |
| FLL07 | 38.9 (4.1)$^{ghi}$ | 23.2 (4.7)$^{defghi}$ | 8 | 13.6 (2.7) |
| HF07 | 43.0 (7.9)$^{fghi}$ | 14.1 (2.3)$^{fghi}$ | 8 | 34.3 (6.3) |
| BLM06 | 81.3 (18.3)$^{bcdefg}$ | 24.9 (3.1)$^{defghi}$ | 13 | 25.2 (6.1) |
| TRN | 121.5 (9.1)$^{ab}$ | 55.9 (6.3)$^{ab}$ | 8 | 14.2 (2.0) |
| APP05 | 157.5 (23.0)$^{a}$ | 46.0 (6.0)$^{abcd}$ | 10 | 25.7 (5.6) |
| TRO | 95.9 (10.6)$^{bcdef}$ | 37.4 (6.2)$^{bcdef}$ | 8 | 38.5 (8.6) |
| APP04 | 16.5 (1.4)$^{hi}$ | 15.5 (2.6)$^{efghi}$ | 9 | 20.0 (3.5) |
| SFR | 115.3 (7.0)$^{abc}$ | 67.1 (5.4)$^{a}$ | 11 | 31.6 (2.5) |
| SHL2 | 61.8 (7.2)$^{defgh}$ | 16.2 (2.3)$^{efghi}$ | 9 | 22.4 (3.6) |
| IMR | 98.9 (15.0)$^{bcde}$ | 18.4 (4.0)$^{efghi}$ | 9 | 19.6 (4.1) |
| MFR | 68.4 (7.4)$^{bcdefgh}$ | 30.7 (5.8)$^{cdefgh}$ | 14 | 13.9 (3.3) |
| STA | 66.4 (8.9)$^{cdefgh}$ | 66.3 (8.0)$^{a}$ | 6 | 31.9 (6.7) |
| WHI | 101.3 (8.7)$^{bcd}$ | 29.4 (3.3)$^{cdefgh}$ | 14 | 13.7 (2.8) |
| APP01 | 47.7 (8.8)$^{efghi}$ | 13.0 (2.7)$^{ghi}$ | 3 | 12.1 (3.6) |
| APP98 | 115.2 (20.0)$^{abc}$ | 37.8 (4.5)$^{bcdef}$ | 11 | 29.8 (5.5) |
| DLB | 4.5 (2.4)$^{i}$ | 1.5 (1.0)$^{i}$ | 3 | 34.0 (3.9) |
| EMB | 4.8 (1.3)$^{i}$ | 1.5 (0.8)$^{i}$ | 6 | 26.6 (3.7) |
| Average | 64.5 (2.9) | 27.4 (1.3) | 9.3 | 30.6 (4.0) |

**Table 3.4** Average height of woody species (± standard error) excluding conifers grouped by traits (Sprouters and Nonsprouters) at 25 masticated fuel treatments in northern California and southern Oregon. P-values reported are based on t-test.

| **Site** | **Sprouter Height (cm)** | **Nonsprouter Height (cm)** | **P-Value** | **Tallest strategy** |
|---|---|---|---|---|
| SLT13 | 34.2 (1.4) | 22.3 (4.3) | **0.0203** | Resprouters |
| EOW | 24.4 (2.8) | 44.6 (6.2) | **0.0062** | Non-sprouters |
| ERR | 42.4 (3.9) | 64.0 (0.0) | * | - |
| VAN | 6.8 (0.6) | 0.0 (0.0) | * | Resprouters |
| SPR11 | 37.1 (3.1) | 33.4 (2.7) | 0.3765 | - |
| SHL | 72.5 (3.2) | 30.4 (5.6) | **<0.0001** | Resprouters |
| HF09 | 40.4 (3.0) | 27.2 (2.1) | **0.0005** | Resprouters |
| JD09 | 41.7 (4.6) | 50.0 (9.4) | 0.4477 | - |
| FLL07 | 44.7 (1.8) | 37.0 (17.0) | 0.7294 | - |
| HF07 | 36.1 (4.6) | 18.1 (1.1) | **0.0003** | Resprouters |
| BLM06 | 45.5 (7.5) | 23.1 (3.3) | **0.0072** | Resprouters |
| TRN | 99.1 (4.7) | 0.0 (0.0) | * | Resprouters |
| APP05 | 100.1 (8.9) | 59.0 (2.5) | **<0.0001** | Resprouters |
| TRO | 92.9 (5.4) | 0.0 (0.0) | * | Resprouters |
| APP04 | 13.0 (0.7) | 19.9 (2.1) | **0.0056** | Non-sprouter |
| SHL2 | 42.6 (3.3) | 40.0 (0.0) | * | - |
| IMR | 31.0 (5.0) | 76.8 (4.8) | **<0.0001** | Non-sprouters |
| MFR | 70.2 (4.2) | 15.7 (2.3) | **<0.0001** | Resprouters |
| SFR | 93.2 (3.3) | 24.4 (14.7) | **<0.0001** | Resprouters |
| STA | 38.9 (3.0) | 89.8 (7.9) | **<0.0001** | Non-sprouters |
| WHI | 65.3 (5.3) | 65.5 (4.6) | 0.9822 | - |
| APP01 | 62.7 (9.8) | 55.5 (5.5) | 0.5273 | - |
| APP98 | 50.1 (4.2) | 87.0 (9.0) | **0.0006** | Non-sprouters |
| DLB | 44.6 (2.9) | 0.0 (0.0) | * | Resprouters |
| EMB | 18.0 (3.8) | 21.3 (1.3) | 0.6794 | - |
| **All Sites** | **57.2 (1.2)** | **46.2 (1.7)** | **0.0001** | **Resprouters** |

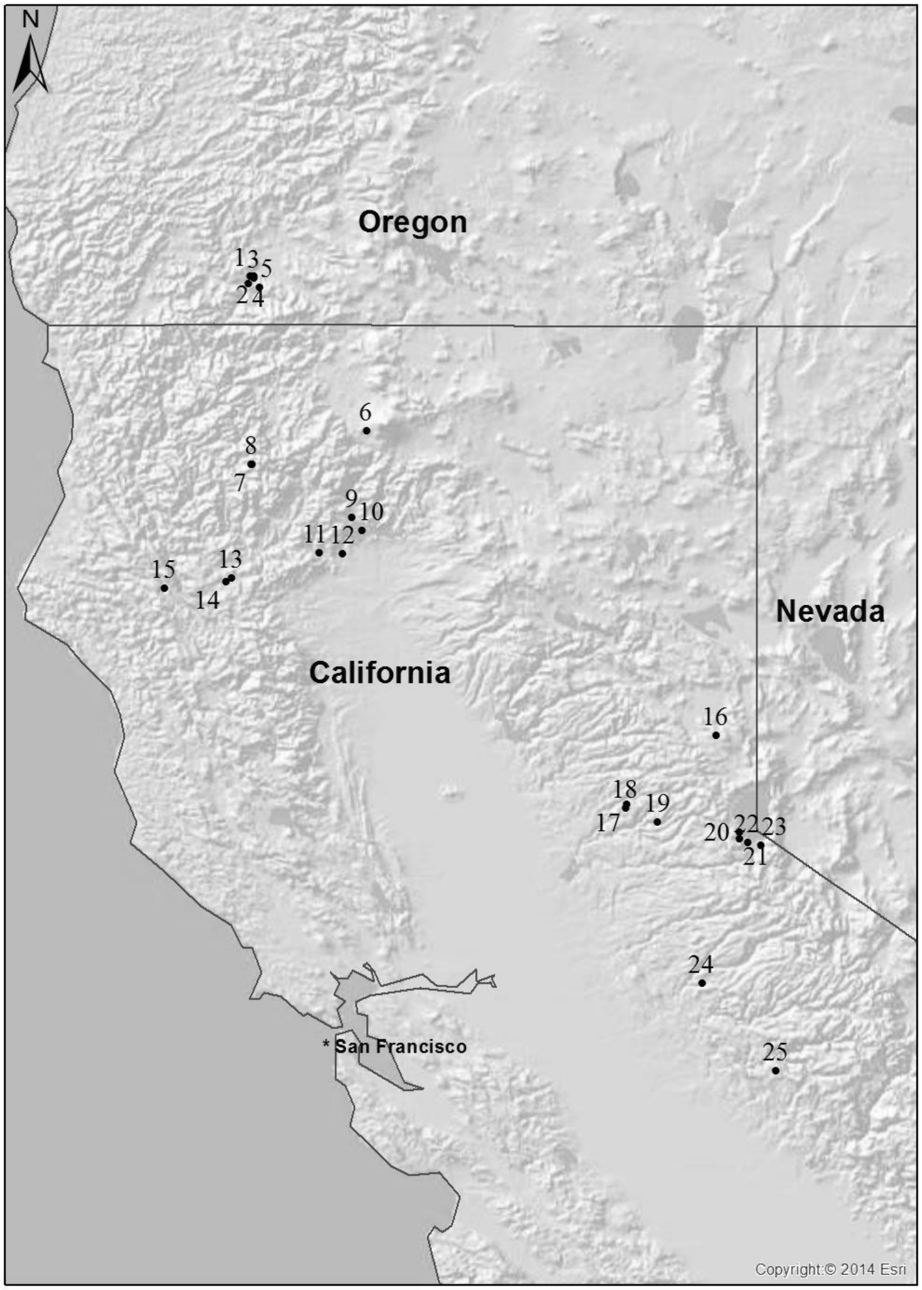


**Figure 3.1** Map of masticated study sites in northern California and southern Oregon, USA.

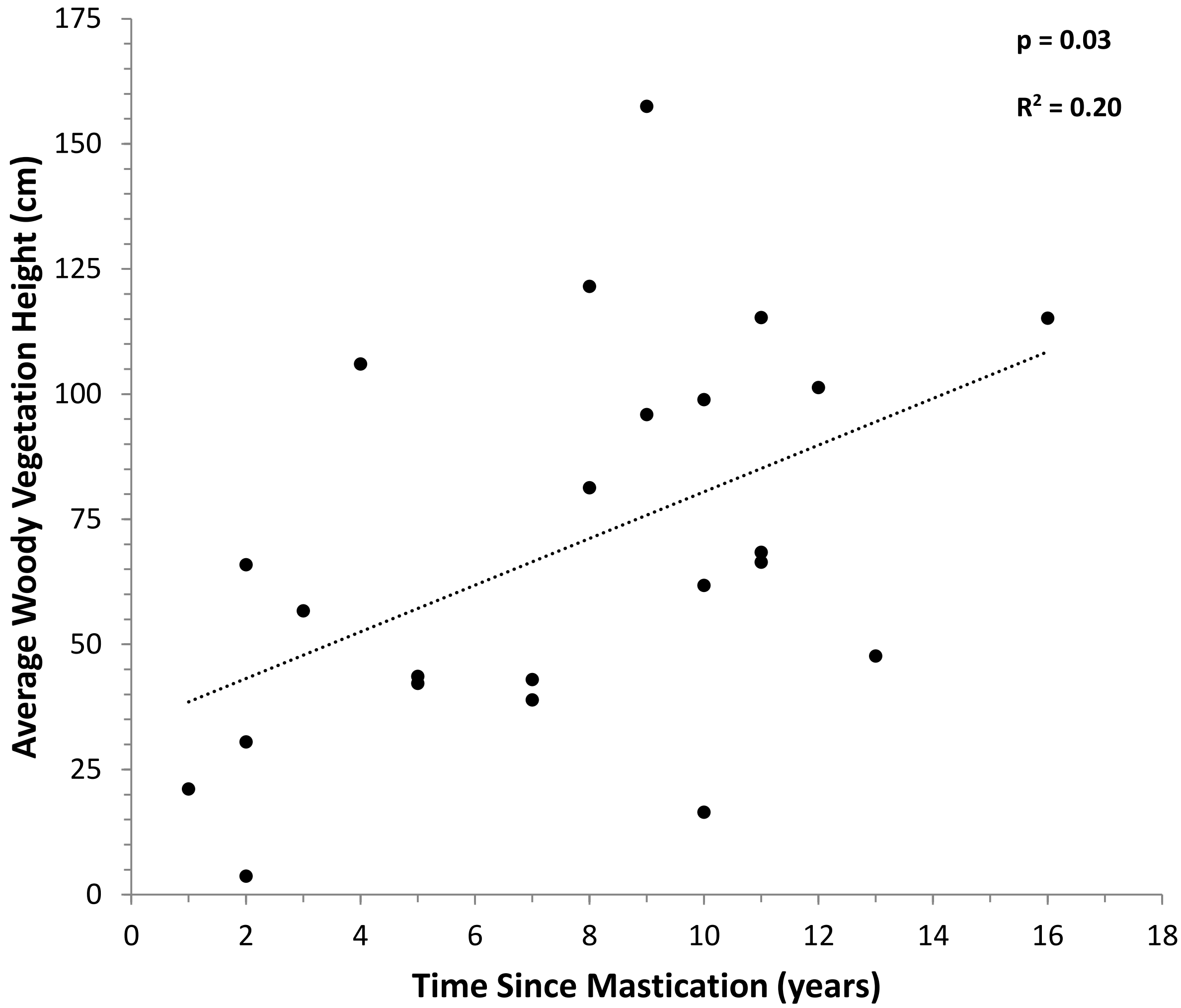


**Figure 3.2** The relationship between average woody vegetation height and time since mastication across 23 sampled sites in northern California and southern Oregon.

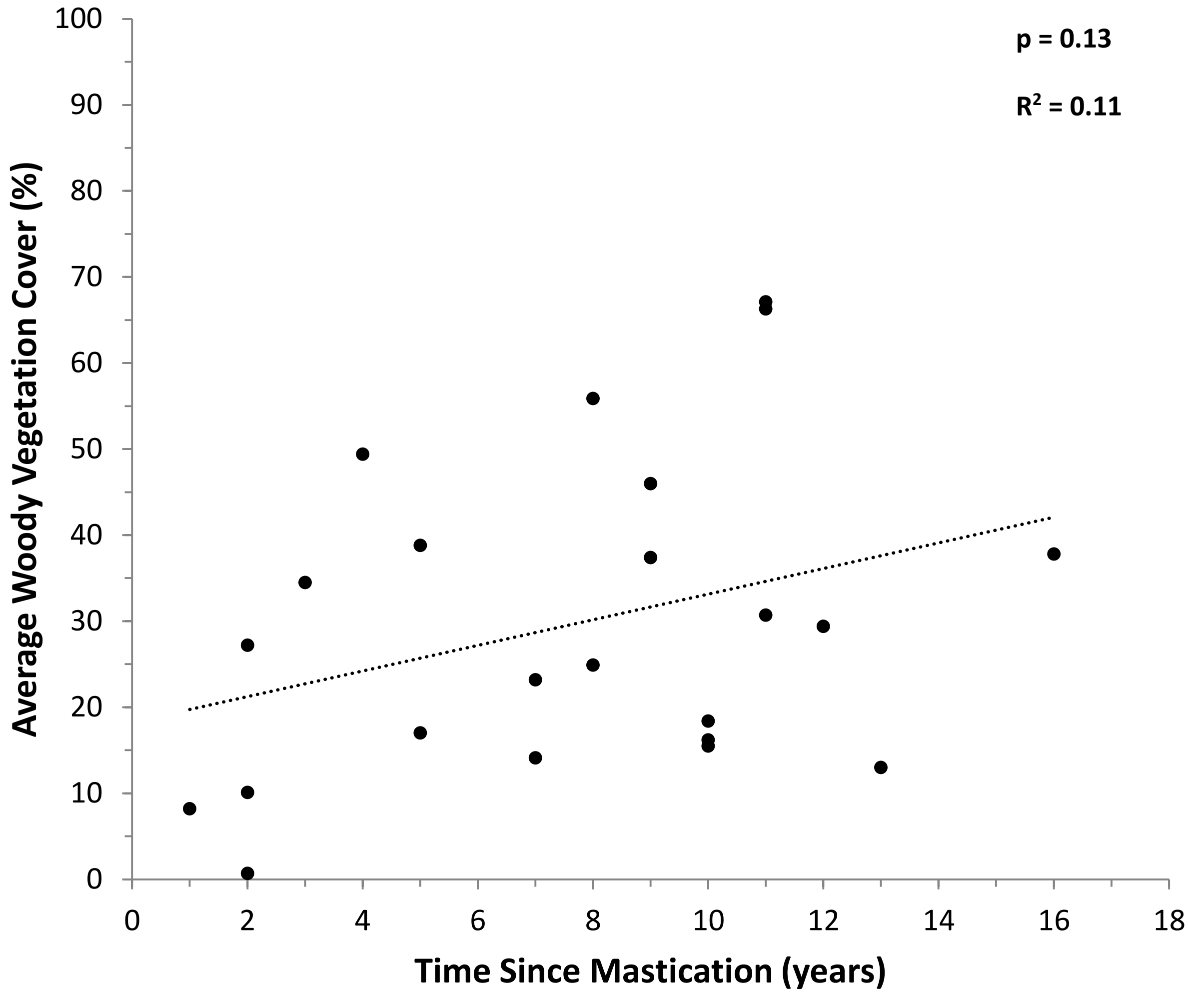


**Figure 3.3** The relationship between average woody vegetation cover and time since mastication across 23 sampled sites in northern California and southern Oregon.

**Figure 3.4** Two masticated field sites with degrees of vegetation recovery. Shown on the left is the EOW site (2 years since mastication) and shown right the TRO site (9 years since mastication).

# CHAPTER 4. CONCLUSIONS

## 4.1 Masticated Fuels Treatments

Fuel treatments in fire-prone landscapes represent an important facet of wildfire management. Mechanical fuel treatments such as mastication are often costly and can yield variable results. Trends of increasing wildfire severity in the face of climate change and past land management are likely to continue to contribute to additional wildfire management challenges (Agee and Skinner 2005, Westerling et al. 2006). A greater understanding of the consequences of masticated fuels can lead to more ecologically sound and cost effective implementation of fuels management. To contribute to this understanding, fuel loading and shrub recovery were estimated at 25 masticated fuel treatments across the fire-prone regions of northern California and southern Oregon.

Results from Chapter 2 provide insight into how masticated woody fuels decline and transition over time. A significant negative relationship between masticated woody fuel mass and time since treatment was hypothesized and detected. The linear relationship used to examine these changes yielded an estimated decrease of 2.4 Mg $ha^{-1}$ per year of masticated woody material across the extensive plot network. At the seven sites where preexisting data on masticated fuels existed from Kane et al. (2009), a more detailed examination of how fuel beds change over time was possible. In the remeasured sites, total fuel loads decreased by an average of 20% between the 8 to 9 year sampling period and 1 and 10-hour fuels decreased on average by 69 and 33 %, respectively. Smaller diameter particles also experienced greater reductions in specific gravity. 1 and 10-hour fuel particles have higher surface area to volume ratios and therefore decompose more rapidly. Future treatments may benefit from faster decomposition rates with increased and tailored operational efforts that result in more small woody masticated fuel particles.

Chapter 3 of this study focused on post-mastication recovery of woody vegetation. Height of recovering woody vegetation was significantly and positively related to time since treatment. Results outlined here reveal that the heights of recovering woody vegetation increase by an average of 8.1 cm per year. The cover of reestablishing woody vegetation was not significantly related to time since mastication. These results highlight the extreme variablilty found in the response to masticate fuel treatments across the study region. Resprouting hardwood shrub and tree species were generally found to gain height more rapidly than nonsprouting species, though the magnitude of difference was small. From a planning perspective, treatments focusing on sites occupied by nonsprouting species may remain more open and gain height slower than sites with resprouting species, and treatments may be effective for longer time periods.

Because both play a role in subsequent fire behavior and effects, examining rates of decomposition of downed masticated material and live vegetation recovery simultaneously offers an important insight into the longevity of masticated fuels treatments. As heavy downed woody fuels decompose, vegetation simultaneously recolonizes masticated sites. Prescribed fire is likely a useful treatment option where possible, and burning under site level tailored prescriptions to decrease surface fuel loads will likely increase treatment efficacy (Stephens and Moghaddas 2005). Because fire behavior is not a linear extrapolation of masticated woody fuel load nor shrub height (Kreye et al. 2014), more research is needed to identify retreatment intervals that take advantage of woody decay while acknowledging the response of flammable shrubs and small trees. Fuel treatment effectiveness also depends on management objectives, and implementation should be considered within the context of place (Brown et al. 2004).

Complications attributed to an observational study design and space for time substitution somewhat challenge the inferential power of this study. In an ideal situation, a long-term repeated measures experiment would be conducted where variables such as pretreatment stand characteristics would be quantified and controlled. Despite these complications, this study reveals a baseline for how masticated fuel treatments transition over time. Future research additionally fusing measures of height and cover to estimate live fuel biomass would contribute towards a greater understanding of the longevity of effectiveness of masticated treatments. The continued and increasing reliance on masticated fuels treatments in fire-prone wildlands warrant further research of the long-term effects of mastication, particularly in fuel treatments that experience wildfire.

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**Appendix A.** Woody species found in masticated fuel treatments in northern California and southern Oregon.

| Genus | Species | Family | Form | Common name |
|---|---|---|---|---|
| *Abies* | *concolor* | Pinaceae | Tree | white fir |
| *Adenostoma* | *fasciculatum* | Rosaceae | Shrub | chamise |
| *Ailanthus* | *altissima* | Simaroubaceae | Tree | tree of heaven |
| *Arbutus* | *menziesii* | Ericaceae | Tree | Pacific madrone |
| *Arctostaphylos* | *manzanita* | Ericaceae | Shrub | Wieslander's manzanita |
| *Arctostaphylos* | *nevadensis* | Ericaceae | Shrub | pinemat Manzanita |
| *Arctostaphylos* | *patula* | Ericaceae | Shrub | greenleaf manzanita |
| *Arctostaphylos* | *viscida* | Ericaceae | Shrub | sticky whiteleaf manzanita |
| *Artemisia* | *tridentata* | Asteraceae | Shrub | big sagebrush |
| *Berberis* | *aquifolium* | Berberidaceae | Shrub | Oregon-grape |
| *Calocedrus* | *decurrens* | Cupressaceae | Tree | incense-cedar |
| *Cercocarpus* | *betuloides* | Rosaceae | Shrub | birchleaf mountain-mahogany |
| *Ceanothus* | *cordulatus* | Rhamnaceae | Shrub | whitethorn ceanothus |
| *Ceanothus* | *cuneatus* | Rhamnaceae | Sub-shrub | buckbrush |
| *Ceanothus* | *integerrimus* | Rhamnaceae | Shrub | deer brush |
| *Ceanothus* | *lemmonii* | Rhamnaceae | Shrub | Lemmon's ceanothus |
| *Cercis* | *occidentalis* | Fabaceae | Tree | California redbud |
| *Ceanothus* | *prostratus* | Rhamnaceae | Sub-Shrub | Mahala mat |
| *Ceanothus* | *pumilus* | Rhamnaceae | Shrub | Siskiyou mat |
| *Ceanothus* | *velutinus* | Rhamnaceae | Sub-shrub | snowbrush ceanothus |
| *Chamaebatia* | *foliolosa* | Rosaceae | Sub-shrub | mountain misery |
| *Chimaphila* | *menziesii* | Ericaceae | Sub-shrub | little prince's pine |
| *Chrysolepsis* | *sempervirens* | Fagaceae | Shrub | bush chinquapin |
| *Cornus* | *nuttallii* | Cornaceae | Tree | mountain dogwood |
| *Eriodictyon* | *californicum* | Hydrophyllaceae | Shrub | yerba santa |
| *Frangula* | *rubra* | Rhamnaceae | Shrub | Sierra coffee berry |
| *Fremontodendron* | *californicum* | Sterculiaceae | Shrub | California flannelbush |
| *Garrya* | *flavescens* | Garryaceae | Shrub | silktassel |
| *Garrya* | *fremontii* | Garryaceae | Shrub | Fremont silk tassel |
| *Heteromeles* | *arbutifolia* | Rosaceae | Shrub | toyon |
| *Lithocarpus* | *densiflorus* | Fagaceae | Tree | tanoak |
| *Lonicera* | *hispidula* | Caprifoliaceae | Sub-shrub | honeysuckle |
| *Pinus* | *attenuata* | Pinaceae | Tree | knobcone pine |
| *Pinus* | *jeffreyi* | Pinaceae | Tree | Jeffrey Pine |
| *Pinus* | *lambertiana* | Pinaceae | Tree | sugar pine |
| *Pinus* | *ponderosa* | Pinaceae | Tree | ponderosa pine |
| *Pinus* | *sabiniana* | Pinaceae | Tree | grey pine |
| *Polygala* | *cornuta* | Polygalaceae | Sub-shrub | milkwort |
| *Prunus* | *emarginata* | Rosaceae | Shrub | bittercherry |
| *Prunus* | *virginiana* | Roseaceae | Shrub | Western choke cherry |
| *Pseudotsuga* | *menziesii* | Pinaceae | Tree | Douglas-fir |
| *Purshia* | *tridentata* | Rosaceae | Shrub | antelope bitterbrush |

| | | | | |
|---|---|---|---|---|
| *Quercus* | *chrysolepis* | Fagaceae | Tree | canyon live oak |
| *Quercus* | *garryana* | Fagaceae | Tree | Oregon white oak |
| *Quercus* | *kelloggii* | Fagaceae | Tree | California black oak |
| *Quercus* | *virginiana* | Fagaceae | Tree | live oak |
| *Quercus* | *wislizeni* | Fagaceae | Tree | interior live oak |
| *Rhamnus* | *californica* | Rhamnaceae | tree/shrub | coffee berry |
| *Rhododendron* | *occidentale* | Ericaceae | Shrub | Western azalea |
| *Rhamnus* | *purshiana* | Rhamnaceae | Shrub | cascara |
| *Ribes* | *aureum* | Grossulariaceae | Shrub | golden current |
| *Ribes* | *roezlii* | Grossulariaceae | Subshrub | Sierra gooseberry |
| *Ribes* | *viscosissimum* | Grossulariaceae | Subshrub | sticky currant |
| *Rosa* | *gymnocarpa* | Rosaceae | Subshrub | wood rose |
| *Rosa* | *woodsii* | Rosaceae | Subshrub | wood rose |
| *Rubus* | *discolor* | Rosaceae | Subshrub | Himalayan blackberry |
| *Rubus* | *laciniatus* | Rosaceae | Subshrub | cut-leaved blackberry |
| *Rubus* | *leucodermis* | Rosaceae | Subshrub | blackcap raspberry |
| *Salix* | *spp* | Salicaceae | Tree/Shrub | willow |
| *Salvia* | *sonomensis* | Lamiaceae | Subshrub | creeping sage |
| *Symphoricarpos* | *mollis* | Caprifoliaceae | Subshrub | creeping snowberry |
| *Symphoricarpos* | *rotundifolius* | Caprifoliaceae | Shrub | roundleaf snowberry |
| *Toxicodendron* | *diversilobum* | Anacardiaceae | Shrub | western poison-oak |
| *Vitis* | *californica* | Vitaceae | Shrub | California wild grape |

**Appendix B.** Linear regression results between litter and woody fuel load (y) and fuel depth (x) across 25 masticated sites in northern California and southern Oregon, USA. Linear regression form: $y = 0 + b_1(x)$; s.e., standard error; probability, $P$

| Site | $n$ | $b_1$ (s.e.) | $P$ |
|---|---|---|---|
| **VAN** | 14 | 7.6 (0.4) | <0.001 |
| **SHL** | 15 | 7.2 (0.7) | <0.001 |
| **JD09** | 15 | 3.4 (0.8) | <0.001 |
| **TRO** | 15 | 7.0 (0.9) | <0.001 |
| **EOW** | 15 | 5.4 (0.5) | <0.001 |
| **HF07** | 15 | 5.0 (0.7) | <0.001 |
| **SPR** | 15 | 3.7 (0.4) | <0.001 |
| **DLB** | 15 | 5.4 (0.6) | <0.001 |
| **STA** | 15 | 3.0 (0.7) | <0.001 |
| **SFR** | 15 | 4.7 (0.6) | <0.001 |
| **APP98** | 14 | 3.7 (0.4) | <0.001 |
| **ERR** | 14 | 3.0 (0.4) | <0.001 |
| **EMB** | 15 | 4.8 (0.5) | <0.001 |
| **SLT13** | 15 | 6.0 (0.4) | <0.001 |
| **APP05** | 15 | 3.4 (0.7) | <0.001 |
| **BLM06** | 15 | 3.3 (0.6) | <0.001 |
| **SHL2** | 15 | 2.2 (0.3) | <0.001 |
| **APP04** | 15 | 2.8 (0.4) | <0.001 |
| **IMR** | 15 | 3.4 (0.8) | <0.001 |
| **TRN** | 15 | 3.1 (0.30 | <0.001 |
| **WHI** | 15 | 1.6 (0.4) | <0.001 |
| **FLL07** | 15 | 2.8 (0.3) | <0.001 |
| **MFR** | 15 | 2.1 (0.6) | <0.001 |
| **HF09** | 13 | 1.0 (0.4) | <0.001 |
| **APP01** | 15 | 2.5 (0.5) | <0.001 |
| **All Sites** | **370** | **4.1 (0.4)** | **<0.001** |