FUEL LOADING AND VEGETATION RESPONSE TO MECHANICAL MASTICATION FUELS TREATMENTS

by

Jeffrey Michael Kane

A Thesis

Presented to

The Faculty of Humboldt State University

In Partial Fulfillment

Of the Requirements for the Degree

Masters of Science

In Natural Resources: Forestry

December, 2007

ABSTRACT

FUEL LOADING AND VEGETATION RESPONSE TO MECHANICAL MASTICATION FUELS TREATMENTS

Jeffrey Michael Kane

Mechanical mastication is a fuels management tool that is increasingly utilized to treat small trees and shrubs in fire-prone ecosystems throughout the western United States. This study characterized fuel loading in masticated fuelbeds across ten sites in northern California and southwestern Oregon. In addition, the vegetation response to mechanical mastication and supplemental fuels treatments was investigated at one study site. Total woody fuel loading of masticated fuelbeds significantly differed by site ($P < 0.001$) ranging between 15.3 and 63.4 Mg ha^{-1}. Over 50% of the woody fuel loading across all sites occurred within the 10-hr timelag class. Additionally, mechanically masticated fuelbeds were distinct compared to existing fuel models, warranting the future development of fuel models specific to masticated fuelbeds. The vegetation response to mechanical mastication treatments varied by treatment type and vegetation measure. Plant cover did not significantly differ across treatment type ($P = 0.062$) but non-native forb density ($P = 0.010$) and diversity ($P = 0.002$) measures did. Mastication only treatments resulted in the highest non-native forb densities (0.8 stems m^{-2}) while mastication followed by prescribed fire resulted in the highest species richness (11.3 species m^{-2}).

ACKNOWLEDGEMENTS

This study was funded through the Joint Fire Science Program, JFSP project #05-2-1-20. My adviser Morgan Varner was very much responsible for directing my efforts, providing good insight, helpful suggestions and constructive criticism. Eric Knapp was equally helpful and considerate, providing me with great input and advice that kept me focused and grounded. John Stuart was helpful in providing sound and sage opinions that often reined me in from doing too much. Much of the chapter one field data collection and sample processing was completed by Elisha Dotson and Emily Orling, with supplemental help from Pong Zhang, Jesse Kreye, and Brad Graham. The field work for my second chapter was graciously and often voluntarily provided by Shanyn Sandhaus, Radoslaw Gleblocki, Christine West, Jesse Kreye, Quentin Stewart, and Andy Goldman; most of whom had to endure poison oak, blackberry prickles, and dense unforgiving thickets of vegetation. Additional thanks goes to both George Pease and Gayleen Smith for providing equipment and administrative support. Dave Young and Robert F. Powers, USDA Forest Service Pacific Southwest Research Station, provided background information on the Challenge Experimental Forest Site and were kind enough to let me sample within the existing experimental design for my chapter on vegetation response. Of course, I would like to generally thank my family and friends, many of who live far away and some that have unfortunately passed. You have all contributed positively to the person I am today and are forever in my thoughts as I am forever in your debt.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

CHAPTER 1

CHAPTER 2

LIST OF TABLES (Continued)

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

LIST OF APPENDICES

CHAPTER 1

CHAPTER 2

CHAPTER 1: Novel fuelbed characteristics associated with mechanically masticated areas in northern California and southwestern Oregon

Introduction

Increases in wildfire size, intensity, and severity, through much of the western United States over the last century, have been primarily attributed to past land management practices such as fire suppression, logging, grazing (Cooper 1960; Biswell 1989; Agee 1993) and, more recently, global climate change (Westerling *et al.* 2006). In many fire-prone ecosystems uncharacteristically heavy surface fuel accumulations and dense, vertically continuous canopies have prompted the need for wildland fuels treatments. While the reintroduction of fire to these ecosystems through prescribed fire or management of natural ignitions is often desirable, many air quality restrictions and safety concerns limit widespread use by land managers. As a result, mechanical methods are becoming increasingly utilized as an initial or solitary fuels management strategy (Agee and Skinner 2005). Mechanical fuels treatments typically utilize traditional timber harvesting equipment to meet fuel treatment objectives; however, areas with non-commercial woody fuels (i.e. small trees, shrubs) require a different strategy.

Mechanical mastication is an increasingly popular method to treat non-commercial woody fuels, especially within fuelbreaks and along the wildland urban interface. Mechanical mastication involves shredding or chipping of small trees and/or shrubs in the midstory and depositing the woody residue on the surface.

Concentration of the woody residue onto the surface results in an increased fuelbed bulk density which can reduce fire behavior through compaction. However, the process of mastication also alters the physical properties of fuel particles which are visually distinct from those of natural or slash-generated fuelbeds. Changes in the physical properties of masticated particles and the fact that these particles often contain fractured and splintered sections will likely result in increased fire behavior (i.e., rate of spread, flame length, fireline intensity) due to probable increases in surface area-to-volume ratios (Rothermel 1972, 1983).

As use of mechanical mastication continues to increase, many questions about the characteristics of these novel fuelbeds have accumulated. In response to these questions this study aimed to:

1) quantify variation in fuel loading across multiple sites in northern California and southwestern Oregon;
2) evaluate the physical properties of masticated fuel particles;
3) determine the relationship between fuel loading and fuelbed depth within and across masticated fuelbed study sites; and
4) compare mechanically masticated fuelbeds to existing fuel models.

Methods

Study Sites

Ten recently masticated sites in northern California and southwestern Oregon were selected to quantify variability in fuel loading (Fig. 1). Study sites were located primarily on federal lands (USDA Forest Service, Bureau of Land Management, and National Park Service) with one additional site on a private forest (Whitmore, California). All mastication treatments used a front-end or boom-mounted masticator with either a rotating drum or blade style head. Treatments were conducted between November 2002 and May 2005 (Table 1). The vegetation masticated within each of the study sites varied but was dominated by shrub species (e.g., *Arctostaphylos* spp., *Ceanothus* spp.) and/or small hardwood tree species (e.g., *Lithocarpus densiflorus*, *Arbutus menziesii*). Data on the ocular estimation of percent relative biomass for each species masticated is provided for shrubs (Appendix A).

Fuel Loading Estimation

Dead woody fuel loading was estimated for each study site using a destructive plot-based sampling method. The plot-based method was accomplished by establishing baseline transects at random azimuths that traversed the treated area within each study site (Fig. 2). At 25 m spacing along the baseline transects, secondary transects were established at a random azimuth. At the 7 m mark of each secondary transect a 50 cm x 50 cm metal frame was placed on the ground and all woody fuels inside the frame were

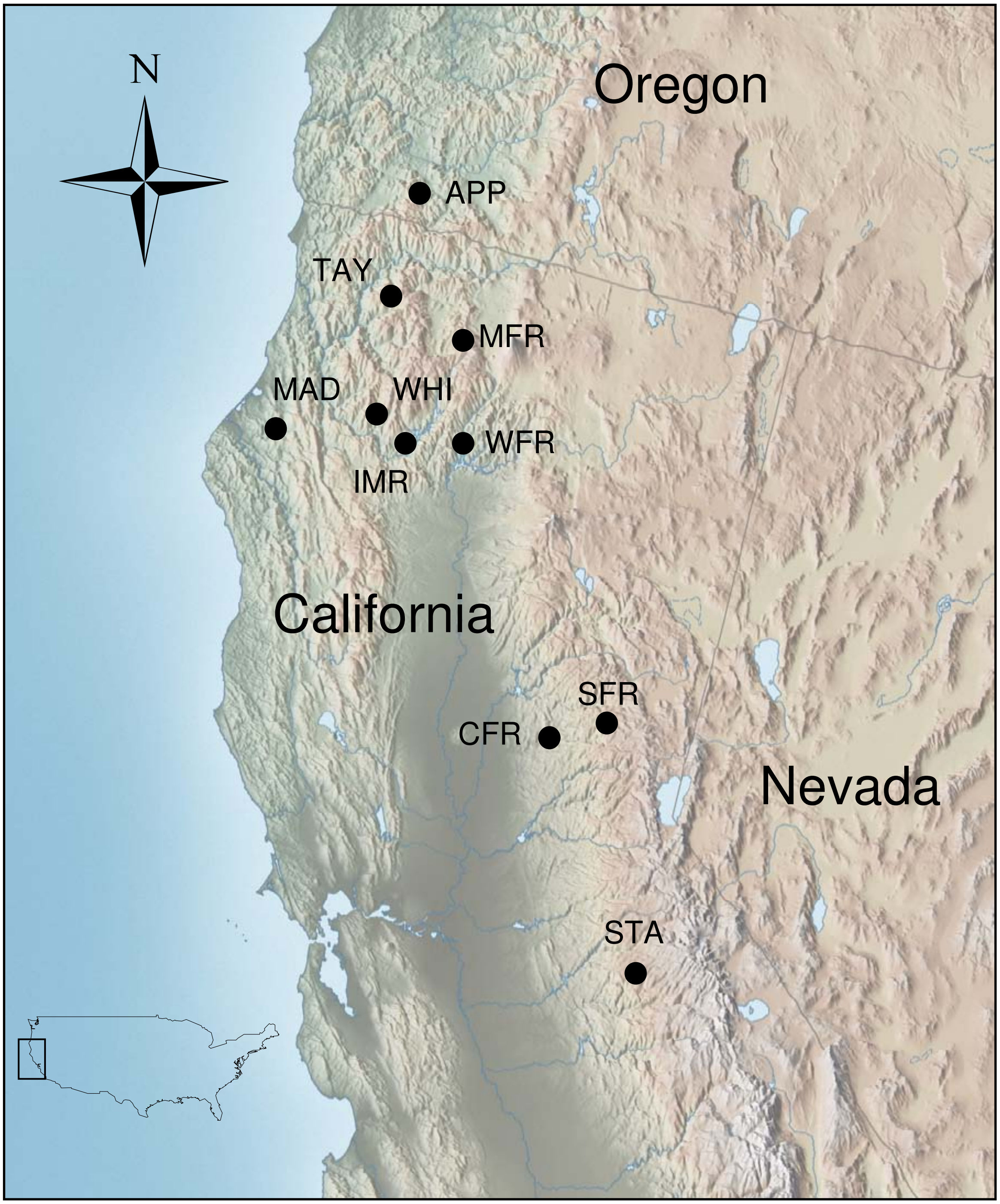

Fig. 1. Study site locations for mechanically masticated areas in northern California and southwestern Oregon, USA.

Table 1. Site names, locations, treatment date, and masticator type for all mechanically masticated study sites in northern California and southwestern Oregon, USA.

Site Code	Site Name	Location	Treatment Date	Masticator Type[A]
APP	Applegate Valley	Applegate Valley, OR (BLM)	Apr./May 2005	BM/RB, Slashbuster brush cutter
CFR	Challenge Fuel Reduction	Plumas National Forest, CA (USFS)	Dec. 2002 Mar. 2003	FE/RD, Rayco Forestry Mower
IMR	Iron Mountain Rd.	Redding, CA (BLM)	Nov. 2004	FE/RD, Masticating head on ASV Positrack
MAD	Mad River	Six Rivers National Forest, CA (USFS)	Dec. 2004	FE/RD, Takeuchi,TL150 w/ FECON Bull hog shredder head
MFR	Mt. Shasta Fuel Reduction	Shasta-Trinity National Forest, CA (USFS)	May 2003	FE/RD, Rayco Forestry Mower (small) on a bulldozer
SFR	Sierraville Fuel Reduction	Tahoe National Forest, CA (USFS)	May/June 2003	FE/RD, Rayco Forestry Mower (small) on a bulldozer
STA	Sampson Fuel Reduction	Stanislaus National Forest, CA (USFS)	Fall 2003	BM/RD, Environmental Forestry head on excavator
TAY	Taylor Ridge	Klamath National Forest, CA (USFS)	Apr./May 2005	BM/RB, Brontasaurus head on excavator
WFR	Whitmore Fuel Reduction	Whitmore, CA (Private)	May 2003	FE/RD, Rayco Forestry Mower (small) on a bulldozer
WHI	Whiskeytown	Whiskeytown NRA, CA (NPS)	Nov. 2002	FE/RB, Slashbuster on an ASV Positrack

[A] BM= boom-mounted, FE = front end mounted; RB = rotary blade, RD = rotary drum

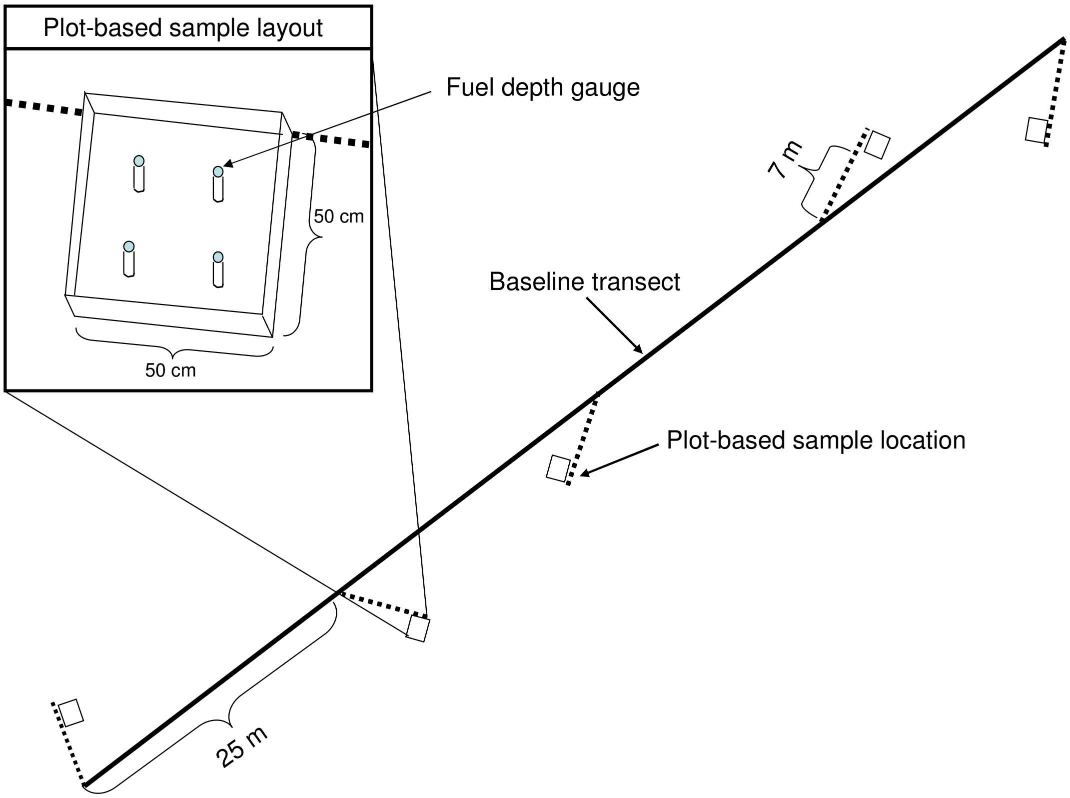

Fig. 2. Surface fuel loading sampling scheme for machine masticated areas of northern California and southwestern Oregon.

collected. In the event that a woody fuel particle crossed the frame, the piece was cut along the boundary and the interior portion retained. All study sites consisted of 15 plot-based samples with the exception of two sites (CFR and WFR) that contained 40 samples each. Prior to fuel removal, fuelbed depth for each plot was determined by pounding four 25 cm large-gauged nails 10 cm diagonally from each of the plot frame corners (Fig. 2) with the nail head flush with the top of the litter/wood layer. Once all four nails were in, the litter/wood layer was removed from the entire plot and the distance from the top of the nail to the bottom of the litter/wood layer was measured. Next, the duff layer was removed and the distance between the top of the nail to the bare mineral soil was measured. To determine duff layer depth, the difference between the two measures was calculated. All woody fuels were separated in the lab by timelag classes, oven-dried for at least 72 hrs at 85ºC in a mechanical convection oven and then weighed on an analytical balance.

The process of mastication results in visually unique particles that differ from natural or slash-based fuel particles. Measures characterizing the physical properties of masticated particles were quantified at each site. These included proportion of fuels with altered surfaces, measures of particle diameter, deviation of particle diameters from a cylinder, and size distributions of particle diameters. To account for geometric irregularities of particles created by mechanical mastication, material collected from three of the plot-based samples for each study site was used to estimate the portion of near-cylinder or regular particles to the proportion of asymmetrical or irregularly shaped particles. Irregular particles were defined as pieces having greater than 50% of the surface area characterized as non-cylindrical due to mastication. In addition, average squared quadratic mean diameters of particles in the 1-hr, 10-hr, and 100-hr timelag classes were obtained by visually dividing each particle into thirds and then taking the minimum and maximum diameters at the midpoint of one of the randomly chosen sections and taking the average of the two measures. Particles measured for diameter were collected from the plot-based method with the number of samples varying based on site and size class. Differences between minimum and maximum diameter measured for each particle was calculated for each timelag class and site. Lastly, distributional curves for average squared quadratic mean diameters were constructed to determine if the particles followed a normal distribution often found in naturally generated fuelbeds (Brown 1974, Brown *et al.* 1982).

Statistical Analyses

Means and standard errors were calculated for site-level estimates of total woody fuel loading and loading by different timelag fuel moisture categories for the plot-based sampling method. Separate one-way analysis of variance (ANOVA) tests were conducted to detect site level differences for mean total woody fuel loading and mean loading by each timelag class. If differences were detected, a post-hoc Bonferoni means comparison test was used to determine which site locations and estimation methods differed from each other (Sokal and Rohlf 1995). If any of the data did not meet the assumptions of normality or equal variance, a square-root transformation of the data was made (Sokal and Rohlf 1995). Furthermore, if transforming the dataset still failed to meet the assumptions of an ANOVA, then a non-parametric Kruskal-Wallis test on ranks, corrected for ties (test value = χ^2) test was completed, followed by a post-hoc Kruskal-Wallis Z-test using the Boneforoni test value. A Shapiro-Wilk W test for normality was performed to determine whether particle diameters were normally distributed within each timelag fuel moisture class for all sites (Sokal and Rohlf 1995).

Pearson's product-moment correlation coefficients (r) and linear regression equations were calculated to determine the relationship between surface fuel loading and fuelbed depth across all sites and for each individual site (Sokal and Rohlf 1995). All statistical tests were computed using NCSS (Hintze 2006), with the level of statistical significance assumed to be $\alpha = 0.05$.

Development of fuel models specific to masticated areas depends on these fuelbeds having distinctive fuel characteristics from existing models. To determine whether masticated fuelbeds investigated in this study were distinct from existing fuel models a cluster analysis was performed in PC-ORD Version 5.0 (McCune and Mefford 1999). A hierarchical, agglomerative cluster procedure was performed using Sorenson distance measures and nearest neighbor group linkage methods to construct a dendrogram relating mechanically masticated fuelbeds to fuel models presented by Anderson (1982). 1 - 13 and all timber (tu and tl) and slash (sb) fuel models from Scott and Burgan (2005). Input data used in the cluster analysis included 1-hr, 10-hr, and 100-hr fuel loading, live fuel loading, and fuelbed depth because of their direct effect on surface fire behavior (Rothermel 1972, 1983).

Results

Fuel Loading Estimation

Dead woody fuel loading estimates from the plot-based method differed significantly by site for all timelag classes ($P < 0.001$; Table 2), with the exception of 100-hr ($\chi^2 = 15.1$, df = 9, $P = 0.089$) and 1000-hr ($\chi^2 = 11.2$, df = 9, $P = 0.264$) timelag classes (Table 2). The highest total woody fuel loading (63.4 Mg ha^{-1}) was observed at the MAD site and was more than 400 percent greater than the lowest fuel loading site (WFR) where the estimated fuel load was 15.3 Mg ha^{-1} (Table 2). Pooled across all sites, fuel loading estimates generated by the plot-based method were largely concentrated in the 10-hr and 1-hr timelag classes, composing 53.7 (± 1.5) and 29.2 (± 1.9) percent of the total woody fuel loading, respectively. Live fuel loading varied significantly among sites, ranging from 0.0 to 6.1 Mg ha^{-1}. Fuel depth varied significantly across sites ($F = 5.02$, df = 8, $P < 0.001$), and ranged from 2.9 to 6.9 cm (Table 2).

Physical Properties of Masticated Particles

The process of mastication resulted in changes of shape, size, and size distribution of fuel particles. For instance, 1-hr fuel loading estimates in masticated sites were primarily composed of particles with irregular shapes (58.7 ± 3.7 percent; Table 3). Many of the particle shapes were better classified as hemi-cylindrical or rectangular rather than round. Larger fuel classes had lower proportions of irregular particles by weight (10-hr = 51.0 ± 4.1 percent, 100-hr = 35.1 ± 7.7 percent). In addition, the presence of a high proportion of surface irregularities translated into stark

Table 2. Comparisons of surface and ground fuel loading measures for mechanically masticated areas from the plot-based sampling method by timelag fuel moisture class and study site. Post-hoc tests were completed with a Kruskal-Wallis multiple comparison z-value test and denoted with superscripted letters, values that share the same letter within each column are not significantly different.

		Plot-based sampling method (50 cm x 50 cm)							
Site	*n*	1-hr	10-hr	100-hr	1000-hr	Total Woody	Live	Litter	Duff
		(Mg ha^{-1})							
APP	15	12.3 (2.8)^{ab}	24.6 (4.9)^{abc}	8.6 (4.9)	5.3 (5.3)	50.7 (10.0)^{ab}	0.0 (0.0)^{c}	10.3 (2.8)^{abc}	6.7 (3.1)^{bc}
CFR	40	7.6 (0.9)^{bc}	21.4 (2.7)^{abc}	8.1 (2.3)	2.2 (1.6)	39.3 (6.1)^{abc}	0.4 (0.3)^{bc}	8.6 (1.1)^{ab}	12.4 (1.8)^{abc}
IMR	15	6.2 (1.7)^{bc}	13.8 (4.0)^{bcd}	3.6 (1.7)	0.0 (0.0)	23.6 (6.9)^{bcd}	0.5 (0.4)^{abc}	2.6 (0.6)^{cd}	7.5 (3.1)^{bc}
MAD	15	23.5 (2.6)^{a}	34.8 (4.3)^{a}	5.1 (2.5)	0.0 (0.0)	63.4 (7.8)^{a}	0.0 (0.0)^{bc}	0.6 (0.3)^{d}	19.6 (4.3)^{ab}
MFR	15	4.7 (1.1)^{bc}	8.2 (2.2)^{cd}	1.3 (0.6)	3.1 (2.2)	17.4 (4.0)^{bd}	0.6 (0.3)^{abc}	2.9 (0.5)^{cd}	15.0 (3.7)^{abc}
SFR	15	5.2 (1.0)^{bc}	11.1 (2.3)^{bcd}	6.6 (2.9)	0.0 (0.0)	22.9 (5.4)^{bcd}	6.1 (2.0)^{a}	5.4 (1.5)^{abc}	5.7 (2.1)^{bc}
STA	15	15.7 (1.7)^{a}	25.0 (3.3)^{ab}	4.8 (1.6)	1.3 (1.3)	46.9 (6.1)^{ac}	1.2 (0.5)^{ab}	9.9 (1.0)^{a}	25.9 (4.0)^{a}
TAY	15	13.2 (2.9)^{ab}	21.7 (4.4)^{abcd}	2.1 (0.8)	0.0 (0.0)	37.0 (6.4)^{abc}	0.6 (0.3)^{abc}	5.6 (1.4)^{abc}	27.9 (5.0)^{a}
WFR	40	4.4 (0.8)^{c}	9.4 (1.7)^{d}	1.6 (0.6)	0.0 (0.0)	15.3 (2.8)^{d}	0.4 (0.2)^{bc}	4.8 (0.5)^{abc}	5.9 (1.2)^{c}
WHI	15	11.8 (2.4)^{ab}	16.4 (2.9)^{abcd}	3.5 (1.5)	0.0 (0.0)	31.8 (5.3)^{abcd}	0.1 (0.1)^{abc}	3.3 (0.7)^{bcd}	7.0 (1.5)^{abc}
P		***< 0.001***	***< 0.001***	*0.089*	*0.264*	***< 0.001***	***< 0.001***	***< 0.001***	***< 0.001***
All Sites		10.5 (1.9)	18.6 (2.7)	4.5 (0.8)	1.2 (0.6)	34.8 (4.9)	1.0 (0.6)	5.4 (1.0)	13.4 (2.7)

Table 3. Surface characteristics of masticated fuel particles as represented by the percent (± SE) by mass of irregular (non-cylindrical) particles for each sample (n = 3) by mastication study site.

	1hr	**10hr**	**100hr**
Site	***% irregular particles***		
APP	42.8 (6.3)	37.5 (10.1)	37.4 (20.6)
CFR	58.7 (4.8)	34.5 (12.3)	39.7 (24.4)
IMR	74.9 (4.9)	51.0 (10.1)	13.7 (7.0)
MAD	82.3 (4.1)	63.0 (7.9)	58.1 (30.0)
MFR	44.8 (5.3)	31.9 (6.6)	33.3 (33.3)
SFR	51.4 (23.7)	79.5 (10.8)	43.7 (29.5)
STA	74.1 (2.7)	51.3 (7.4)	0.0 (0.0)
TAY	54.0 (8.0)	57.5 (12.2)	0.0 (0.0)
WFR	44.1 (8.7)	54.9 (22.2)	84.3 (15.7)
WHI	60.3 (16.9)	48.6 (15.6)	34.7 (22.7)
All Sites	58.7 (3.7)	51.0 (4.1)	34.7 (8.1)

differences between the minimum and maximum diameter of masticated particles. The percentage differences between maximum and minimum diameters were 42.2 ± 1.5, 34.9 ± 1.2, and 29.0 ± 3.0 percent for 1-hr, 10-hr, 100-hr fuels, respectively.

Squared average quadratic mean diameters varied significantly among sites for both 1-hr (χ^2 = 404.5, df = 9, $P < 0.001$) and 10-hr timelag classes (χ^2 = 58.8, df = 9, $P < 0.001$). One hour timelag diameter values for masticated fuels at some sites were twice the standard input value. The reverse was true for the 10-hr and 100-hr time lag classes (Table 4). In addition, the squared average quadratic mean diameters were not normally distributed across all ten sites for 1-hr and 10-hr fuel classes. Shapiro-Wilk W test values ranged from 0.58 to 0.81 (Table 4) with positively skewed ($g_1 > 0$) and leptokurtic ($g_2 > 0$) distributional properties (Sokal and Rohlf 1995). The 100-hr timelag fuels were normally distributed with the exception of three sites (CFR, SFR, and WHI) though this fuel class also had much smaller sample sizes ($n < 17$) across all sites (Table 4).

Fuel Loading and Depth Relationships

The relationship between total woody and litter fuel loading and depth from plot-based estimates was not significant across all sites ($r = 0.61$, $P = 0.081$; Fig. 3). Regressions for data among plots within individual sites revealed that all but two sites had a significantly positive relationship between load and depth (Table 5). Correlation coefficients (r) for fuel depth:load relationships varied substantially by site ranging between 0.09 and 0.94 (Table 5). STA and MAD fuel load estimates showed the strongest relationships with

Table 4. Fuel particle diameters (d^2) and distributions of 1-hr, 10-hr, and 100-hr timelag classes for ten mastication study sites in northern California and southwestern Oregon. Values represent square quadratic mean diameter (mean ± SE) and Shapiro-Wilk (W) test of normality.

	1-hr Timelag Class				10-hr Timelag Class				100-hr Timelag Class			
			Normality				*Normality*				*Normality*	
	n	d^2	*W*	*P*	*n*	d^2	*W*	*P*	*n*	d^2	*W*	*P*
Site		*Cm²*				*cm²*				*cm²*		
APP	405	0.12 (0.01)^{bc}	0.80	***< 0.001***	150	1.53 (0.13)^{bc}	0.62	***< 0.001***	9	13.5 (2.3)	0.85	0.073
CFR	364	0.17 (0.01)^{a}	0.75	***< 0.001***	294	1.70 (0.08)^{ab}	0.80	***< 0.001***	15	12.5 (1.6)	0.76	***0.001***
IMR	561	0.15 (0.01)^{ab}	0.81	***< 0.001***	164	1.39 (0.10)^{bc}	0.67	***< 0.001***	7	11.4 (1.0)	0.86	0.143
MAD	1210	0.09 (0.00)^{d}	0.60	***< 0.001***	147	1.36 (0.10)^{bc}	0.72	***< 0.001***	4	11.9 (1.5)	0.95	0.734
MFR	604	0.13 (0.01)^{bc}	0.70	***< 0.001***	262	1.41 (0.08)^{bc}	0.70	***< 0.001***	4	13.3 (1.6)	0.89	0.404
SFR	444	0.13 (0.01)^{bc}	0.67	***< 0.001***	231	2.21 (0.15)^{a}	0.69	***< 0.001***	17	19.7 (3.6)	0.78	**0.001**
STA	728	0.14 (0.01)^{abc}	0.58	***< 0.001***	266	1.51 (0.08)^{bc}	0.71	***< 0.001***	7	13.6 (1.7)	0.96	0.832
TAY	855	0.13 (0.01)^{bc}	0.74	***< 0.001***	252	1.19 (0.06)^{c}	0.71	***< 0.001***	6	13.8 (1.8)	0.96	0.845
WFR	666	0.15 (0.01)^{abc}	0.75	***< 0.001***	157	1.41 (0.13)^{bc}	0.53	***< 0.001***	5	16.6 (1.4)	0.98	0.920
WHI	660	0.12 (0.01)^{c}	0.73	***< 0.001***	167	1.59 (0.12)^{bc}	0.70	***< 0.001***	2	16.6 (10.0)	0.75	**< 0.001**
P		***< 0.001***				***< 0.001***				0.598		
All Sites		0.13 (0.007)			10	1.53 (0.09)			10	14.3 (0.8)		
Default (Brown 1974)		0.10				1.87				17.8		

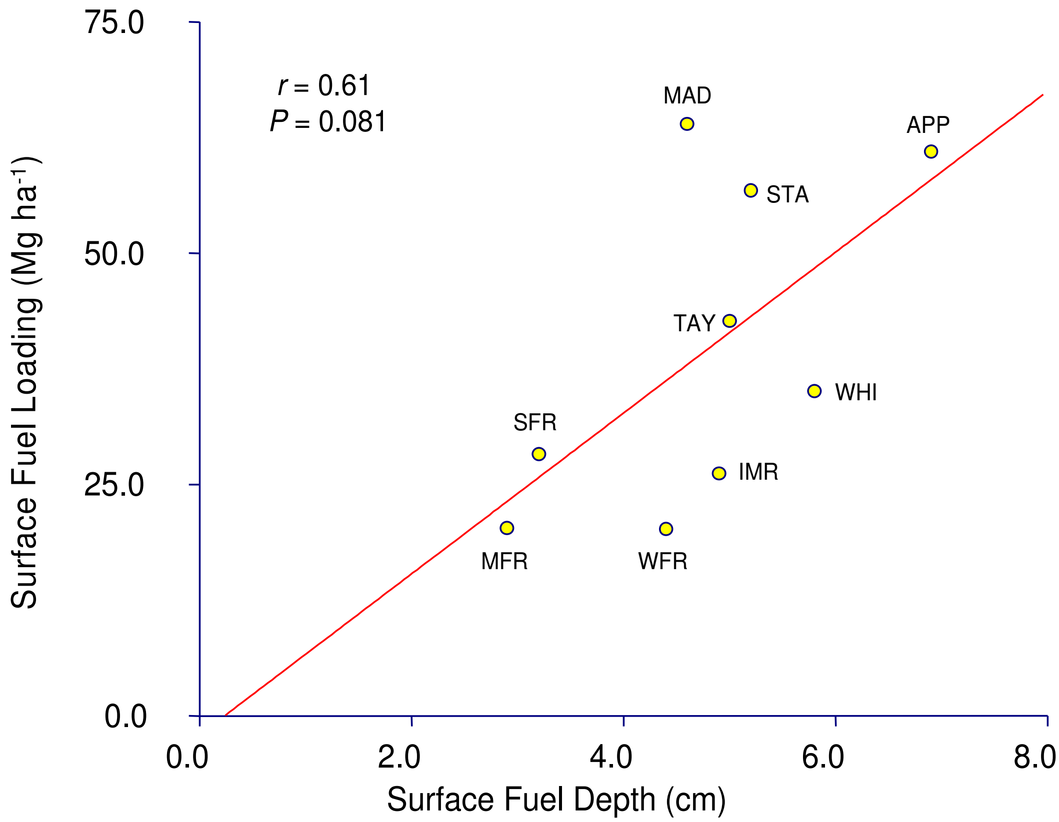

Fig. 3. Relationship between surface fuel depth (cm) and surface (woody + litter) fuel loading (Mg ha^{-1}) across mastication study sites. The equation of the line shown is: surface fuel loading = -2.05 + (8.70) surface fuel depth.

Table 5. Linear regression results between fuel depth (x) and litter/woody fuel load (y) for across masticated sites in northern California and southwestern Oregon.

Site	*n*	Linear Equation	*r*	*P*
APP	15	y = (-1.7797) + (9.1362) x	0.62	***0.013***
IMR	15	y = (-10.6152) + (7.4747) x	0.81	***< 0.001***
MAD	15	y = (-5.8889) + (15.2514) x	0.92	***< 0.001***
MFR	15	y = (23.8260) + (-1.2149) x	0.11	*0.694*
SFR	15	y = (-8.5933) + (11.6902) x	0.94	***< 0.001***
STA	15	y = (14.6215) + (8.1692) x	0.67	***0.006***
TAY	15	y = (-1.7357) + (8.9032) x	0.77	***< 0.001***
WFR	40	y = (17.0117) + (0.7249) x	0.09	*0.576*
WHI	15	y = (-7.5351) + (7.3307) x	0.75	***0.001***
All Sites	9	y = (-2.0477) + (8.6953) x	0.61	*0.081*

fuel depth, $r = 0.94$ and 0.92 respectively. The weakest relationships were found at the MFR and WFR sites, with r values of 0.09 and 0.11, respectively.

Fuel Model Comparisons

Mechanically masticated fuelbeds formed a distinct group relative to other fuel model types based on cluster analysis (Fig. 4). All mastication sites within the study partitioned from the other fuel models and clustered together forming an obvious group. Within the mastication sites themselves, three potentially distinct groups based on fuelbed characteristics were observed. The first division within masticated sites was seemingly based on the presence of live fuel loading greater than 5 Mg ha^{-1} (SFR), while the other groups were divided generally by low (IMR, MFR, WFR) and high (MAD, APP, TAY, STA, CFR, WHI) fine fuel loading (Fig. 4).

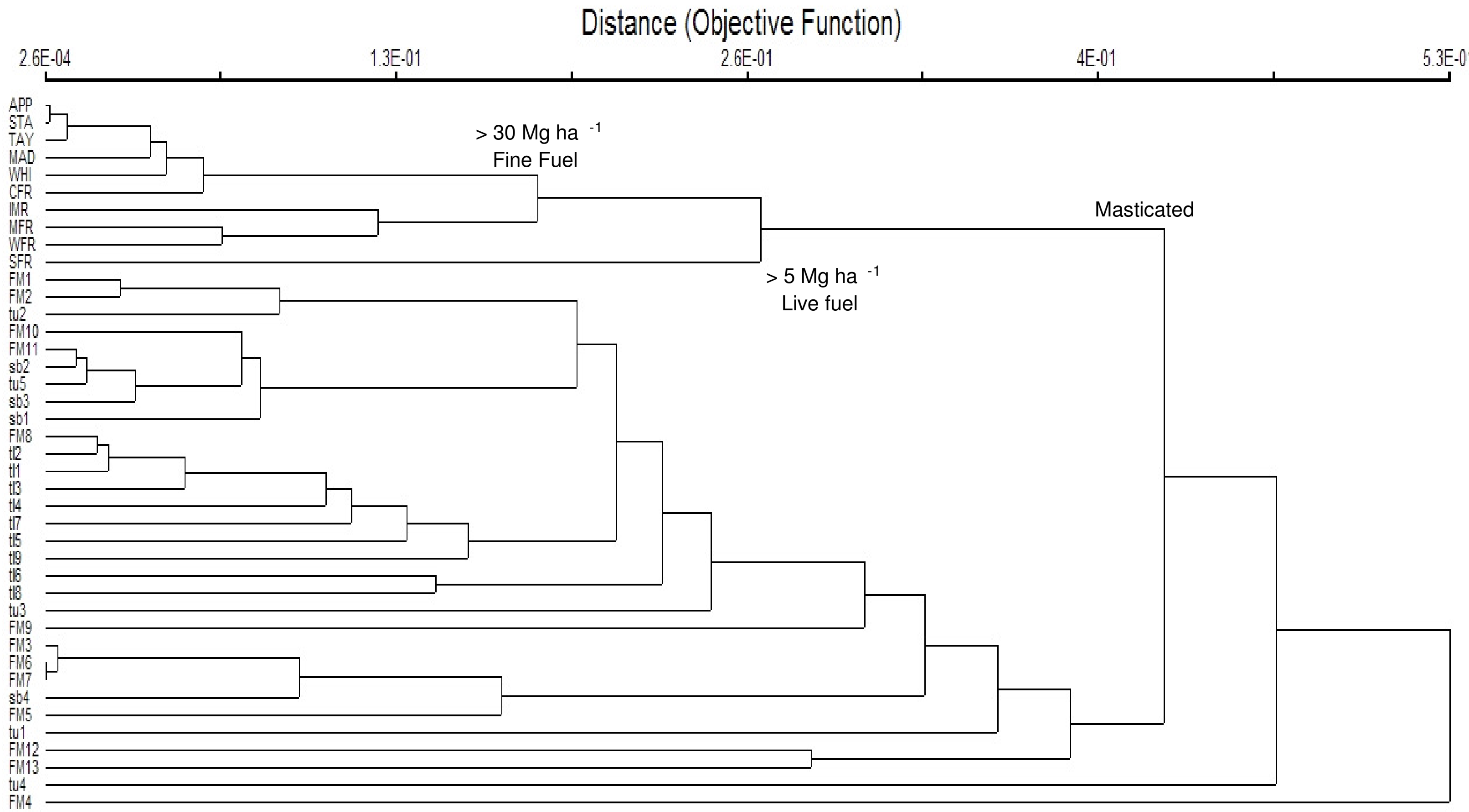

Fig. 4. Dendrogram of cluster analysis classification of mechanically masticated fuelbeds in northern California and southwestern Oregon (by site) compared to existing fuel models: NFFL-FM 1-13 (Anderson 1982); and tu 1-5, tl l-9, and sb 1-4 (Scott and Burgan 2005).

Discussion

Fuel Loading Estimation

Few studies have quantified fuel loading of mechanically masticated sites in spite of its increased utilization throughout much of the western United States. Total dead woody fuel loading estimates in this study ranged widely (15.8 to 65.5 Mg ha^{-1}) but were similar to reported estimates in other studies within masticated areas, such as, the northern Rocky Mountains by Hood and Wu (2006), (39.0 to 56.0 Mg ha^{-1}) and the southern Sierra Nevada by Stephens and Moghaddas (2005), (38.0 Mg ha^{-1}).

Total woody fuel loading and loading by individual timelag classes differed significantly across ten sites in northern California and southwestern Oregon (Table 2). The probable reason for these differences in total woody fuel loading was likely due to differences in pretreatment biomass and the percentage of biomass treated. The amount of pretreatment biomass varies with stand age, time since last disturbance, site productivity (i.e. soil moisture and nutrient availability), vegetation type, and species composition. While differences exist in total woody loading across sites, most sites were similar in the proportion of woody loading in different fuel size classes. Almost all sites had the greatest proportion of loading concentrated within the 1-hr and 10-hr timelag classes, collectively making up more than 80% of the woody load (Table 2). Concentration of the woody fuels into fine fuel classes is the direct result of the chipping and shredding conducted by the masticating head and will likely vary depending on type of masticator, style of the operator, and type of vegetation being masticated.

Physical Properties of Masticated Particles

Mechanical mastication specifically results in the creation of smaller, non-cylindrical fuel particles. The preponderance of load found within fine fuel classes has direct implications for fire behavior and fire effects within masticated fuel types. Not only are most of the masticated particles small, but many are often fractured and splintered. These two features both represent particles with larger surface area-to-volume ratios. As the surface area-to-volume ratio increases the ability for the particle to gain or lose moisture increases (Lancaster 1970). Both decreases in the response rate and increases in surface area-to-volume ratios of particles will increase ignitability, sustainability, combustibility and consumability of particles (Anderson 1970; Martin *et al.* 1993). Subsequently, particles with increased surface area-to-volume ratios and lower response rates may contribute to higher rates of spread, flame length and fireline intensity compared to larger particles with lower surface area-to-volume (Rothermel 1972, 1983).

While many features of masticated fuelbeds may increase fire behavior, the compacted nature of masticated fuelbeds may act to ameliorate fire behavior with greater fuelbed bulk densities reducing the amount of oxygen entering the fuelbed. This may reduce the rate of spread, flame length, and fireline intensity associated with flaming combustion. However, an increase in fuelbed bulk density may result in increases in smoldering combustion and heat duration. Increases in the amount of smoldering combustion may result in increased smoke production and increased tree mortality due to root death or cambial girdling.

The discovery of differences in squared quadratic mean diameter by site, deviations in particle shape from a cylinder, and non-normally distributed size particles all violate assumptions necessary for accurate fuel loading estimates using the planar intercept method (Van Wagner 1968; Brown 1974; Brown *et al.* 1982). While this study used the destructive plot-based method, many researchers and managers often rely on the planar intercept method for efficient sampling of fuel loading. Use of the planar intercept method has even been used to quantify fuel loading specifically in masticated areas (Stephens and Moghaddas 2005; Hood and Wu 2006). Violations in the assumptions of the planar intercept method may result in inaccurate predictions of both fire behavior and effects (van Wagtendonk *et al.* 1996). Since researchers have noted difficulties in accurately predicting fire behavior in masticated fuel beds (Bradley *et al.* 2006, Glitzenstein *et al.* 2006, Knapp *et al.* 2006), one possible explanation may be related to inaccurate fuel loading estimates. Further studies investigating the appropriateness of using the planar intercept method to estimate fuel loading in masticated fuelbeds are necessary to assure accurate fire behavior predictions.

Fuel Loading and Depth Relationships

The ability to estimate fuel loading from simple measures such as fuelbed depth would substantially reduce the resources necessary to acquire such data. Other fuel types have accurately used surrogate measures to estimate fuel loading (Fulé and Covington 1994). However, this study suggests that, in general, fuel depth is not a significant predictor of woody and litter fuel loading across all masticated sites surveyed (Fig. 6). For instance, some sites (e.g., MAD, SFR) exhibited a strong positive relationship ($r > 0.90$) between depth and load, while others had a weaker relationship and were not significant (Table 8). The two sites with the poorest relationship (MFR and WFR) also had the lowest total woody fuel loading values, suggesting that the relationship between fuel depth and load may be a function of the amount of load. For instance, sites with lower loading values may also have more heterogeneous distributions of fuel across the site causing greater variability in the total loading estimate with smaller sample size. However, this possibility was not supported based on results of a correlation analysis between the depth/load correlation coefficients and the coefficient of variation of each site ($r = 0.14$, $P = 0.727$). In general, the indiscriminant use of fuel depth as a surrogate measure of loading in masticated sites is not warranted and must be evaluated on a site-by-site basis. While the use of site-by-site equations to estimate load may be accurate, depending on the strength of the relationship, the utility for managers is lost due to the time-intensive nature of sampling fuels at each site. One major factor that may contribute to evaluating the utility of fuel depth: load relationships in estimating load is by grouping them into plant community types. For instance, Hood and Wu (2006) found differences in the correlation coefficients based on plant community type. *Pinus jeffreyi* - *Abies concolor* ($r = 0.86$) and *Pinus ponderosa* –*Quercus gambelii* ($r = 0.65$) types had relatively good depth to load relationships, while *Pinus edulis* – *Juniperus osteosperma* ($r = 0.29$) had a poorer relationship. However, other factors such as mastication equipment, proportion of biomass masticated, and stand age are also contributing factors to this relationship.

Fuel Model Comparisons

Differences in woody fuel loading, fuel depth, and live fuel loads among the ten mastication study sites (Table 5) suggest that multiple fuel models may be necessary to accurately characterize fire behavior in masticated fuel types. This conclusion is further supported by the cluster analysis classification (Fig. 7), where masticated fuelbeds were grouped separately from existing fuel models (Anderson 1982, Scott and Burgan 2005). Within masticated fuelbeds of northern California and southwestern Oregon, differentiation of fuelbeds occurred based on total fine woody load and live fuel loading.

Total fine woody (1-hr-100-hr) and litter fuel loading estimates in machine masticated fuelbeds ranged widely from 19.6 to 66.1 Mg ha^{-1} and most closely resembled total loading in slash based fuel models from Anderson (1982) and Scott and Burgan (2005). While overall loading estimates were similar, masticated fuelbeds differed from these models in two distinct and consistent ways. Masticated fuelbeds were much more compacted. Fuelbed depth (2.9 to 6.9 cm) was an order of magnitude less than fuelbed depth in existing slash based models (30.0 to 90.0 cm) in which these measures reflect large differences in the packing ratio of the fuelbeds. In addition, the contribution of load in masticated fuelbeds was more heavily concentrated in the 10-hr timelag class (53.4%) compared with the slash models (range = 10 to 40%). While greater proportions of fuel loading in finer fuel classes might be expected to result in more intense fire behavior (i.e. flame length, rate of spread), fuelbed compaction is predicted to moderate fire behavior and has been shown to reduce tree mortality with burning (Jerman *et al.* 2004). However, both of these features can cause extended heat duration and greater incidence of smoldering combustion (Busse *et al.* 2005), potentially promoting negative effects such as elevated smoke production and tree mortality, seed bank depletion, and non-native plant establishment following fire.

The use of mechanical mastication is likely to continue to expand throughout many of the fire-prone regions in the western United States. Unlike other fuels treatments, mechanical mastication does not remove fuel from the area but rather concentrates it on the surface of the treated areas. Research that quantifies the surface fuel accumulations within treated areas is paramount to fully evaluating mechanical mastication as a viable fuels treatment option. In tandem with this research is the need to develop models that can predict fire behavior and effects within these novel fuel types. The number of fuel models necessary to adequately encompass the variation of masticated fuelbeds is not completely understood, however, results of this research suggest that multiple fuel models may be necessary. The development of these models will assist land managers in their ability to predict the behavior and effects of fire in masticated fuelbeds.

References

Agee JK (1993) 'Fire ecology of Pacific Northwest forests'. (Island Press: Washington DC)

Agee JK, Skinner C (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83-96.

Anderson HE (1970) Forest fuel ignitability. *Fire Technology* **6**, 312-319.

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, Intermountain Research Station, General Technical Report INT-122. (Ogden, UT)

Biswell HH (1989) 'Prescribed Burning in California Wildlands Vegetation Management'. (University of California Press: Berkeley, CA)

Bradley T, Gibson J, Bunn W (2006) Fuels management and non-native plant species: an evaluation of fire and fire surrogate treatments in a chaparral plant community. Final Report to the Joint Fire Science Program. Available at http://www.firescience.gov/projects/01B-3-3-27/01B-3-3-27_final_report.pdf.

Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-16. (Ogden, UT)

Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-129. (Ogden, UT)

Busse MD, Hubbert KR, Fiddler GO, Shestak CJ, Powers RF (2005) Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* **14**, 1-10.

Cooper CF (1960) Changes in vegetation, structure and growth of south-western pine forests since white settlement. *Ecological Monographs* **30**, 129-164.

Fulé, PZ, Covington WW (1994) Double sampling increases the efficiency of forest floor inventories for Arizona ponderosa pine forests. *International Journal of Wildland Fire* **170,** 19–41.

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

Hickman JC (1993). 'The Jepson manual: higher plants of California'. (University of California Press: Berkeley, CA)

Hintze JL (2006) Number crunching statistical systems, Version 2006 (Kaysville, UT)

Hood S, Wu R (2006) Estimating fuelbed loading in masticated areas. In 'Fuels Management—How to measure success: Conference Proceedings' (compilers PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41. pp. 333-340. (Fort Collins, CO)

Jerman JL, Gould PJ, Fulé PZ (2004) Slash compression treatment reduced tree mortality from prescribed fire in southwestern ponderosa pine. *Western Journal of Applied Forestry* **19**, 149-153.

Knapp EE, Busse MD, Varner JM, Skinner CN, Powers RF (2006) Behavior and short-term effects of fire in masticated fuelbeds. In 'Proceedings of the Third International Fire Ecology and Management Congress'. Nov. 13-17, San Diego, CA. Available at http://www.fs.fed.us/psw/programs/ecology_of_western_forests/publications/publications/Knapp_AFE2006.pdf [verified 23 Oct 2007]

Lancaster JW (1970) Timelag useful in fire danger rating. *Fire Control Notes* **31**, 6–8.

Martin RE, Gorden DA, Gutierrez ME, Lee DS, Molina DM, Schroeder RA, Sapsis DA, Stephens SL, Chambers M (1993) Assessing the flammability of domestic and wildland vegetation. Proceedings of the 12th Conference on Fire and Forest Meteorology, October 26-28. pp. 130-137. (Jekyll Island, GA)

McCune B, Mefford MJ (1999) PC-ORD. Multivariate analysis of ecological data, Version 5.0. MjM Software. (Gleneden Beach, OR)

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115. (Ogden, UT)

Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-143. (Ogden UT)

Scott JH, Burgan RE (2005) Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service, Rocky

Mountain Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO)

Sokal RR, Rohlf FJ (1995) ‘Biometry: The principles and practice of statistics in biological research’. 3rd edition. (W. H. Freeman and Co: New York, NY)

Stephens SL, Moghaddas JJ (2005) Experimental fuel treatment impacts on forest structure, potential fire behavior and predicted tree mortality in Californian mixed conifer forest. *Forest Ecology and Management* **215**, 21-36.

Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **14**, 20-26.

van Wagtendonk JW, Benedict JM, Sydoriak WM (1996) Physical properties of woody fuel particles of Sierra Nevada Conifers. *International Journal of Wildland Fire* **6**, 117-123.

Westerling AL, Hildalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science* **313**, 940-943.

Appendix A: Estimated percent shrub biomass masticated based on ocular estimates of adjacent untreated areas by species within ten study sites of northern California and southwestern Oregon.

Site Code	Biomass (%)	Scientific Name*
APP	63.3	*Toxicodendron diversilobum*
	20.0	*Quercus kellogii*
	8.3	*Quercus garryana*
	3.7	*Ceanothus cuneatus*
	3.7	*Ceanothus integerrimus*
	1.0	*Arctostaphylos viscida*
	1.0	*Cercocarpus betuloides*
IMR	77.8	*Arctostaphylos viscida*
	20.0	*Heteromeles arbutifolia* var. *cerina*
	1.3	*Ailanthus altissima*
	1.0	*Toxicodendron diversilobum*
MAD	100.0	*Arctostaphylos manzanita* ssp. *manzanita*
MFR	95.0	*Arctostaphylos patula*
	2.0	*Ceanothus velutinus* var. *velutinus*
	0.8	*Chrysolepsis sempervirens*
	0.5	*Ceanothus prostratus*
	0.4	*Purshia tridentata*
	0.3	*Chrysothamnus* sp.
	0.1	*Prunus emarginata*
	0.1	*Salvia sonomensis*
SFR	90.0	*Ceanothus velutinus* var. *velutinus*
	1.5	*Arctostaphylos patula*
	1.5	*Ceanothus prostratus*
	1.5	*Prunus emarginata*
	1.5	*Ribes aureum*
	1.5	*Salix* sp.
	1.5	*Symphoricarpos rotundifolius* var. *rotundifolius*
	0.5	*Ceanothus cordulatus*
	0.5	*Chrysolepsis sempervirens*
STA	95.7	*Arctostaphylos viscida*
	0.8	*Quercus chrysolepis*
	0.5	*Chamaebatia foliolosa*
	0.5	*Heteromeles arbutifolia* var. *cerina*
	0.5	*Toxicodendron diversilobum*
	0.3	*Ceanothus integerrimus*

* nomenclature follows Hickman (1993)

Appendix A (cont.): Estimated percent shrub biomass masticated based on ocular estimates of adjacent untreated areas by species within ten study sites of northern California and southwestern Oregon.

Site Name	Biomass (%)	Scientific Name*
TAY	75.0	*Ceanothus velutinus* var. *velutinus*
	16.8	*Arctostaphylos patula*
	5.3	*Chrysolepsis sempervirens*
	3.3	*Salix* sp.
	0.2	*Ribes roezlii*
	0.2	*Ribes* sp.
	0.2	*Symphoricarpos mollis*
WFR	47.8	*Arctostaphylos viscida*
	37.8	*Arctostaphylos manzanita* ssp. *weislanderi*
	8.9	*Toxicodendron diversilobum*
	2.8	*Ceanothus prostratus*
	2.5	*Quercus kelloggii*
	0.8	*Ceanothus lemmonii*
	0.3	*Rhamnus californica* ssp. *californica*
	0.1	*Berberis aquifolium*
	0.1	*Garrya flavescens*
WHI	78.8	*Arctostaphylos viscida*
	12.3	*Heteromeles arbutifolia* var. *cerina*
	2.0	*Ceanothus lemmonii*
	1.5	*Adenostoma fasciculatum*
	1.5	*Toxicodendron diversilobum*
	1.0	*Lonicera* sp.
	0.8	*Fremontodendron californicum*
	0.8	*Salvia sonomensis*
	0.5	*Cercis occidentalis*
	0.5	*Quercus chrysolepis*
	0.3	*Eriodictyon californicum*
	0.3	*Quercus wislizenii*

* nomenclature follows Hickman (1993)

CHAPTER 2: Initial vegetation response to mechanical mastication fuels treatments in a northern Sierra Nevada ponderosa pine forest.

Introduction

Decades of fire exclusion and past logging activities have altered the forest structure, composition, and ecological function in most *Pinus ponderosa* forests. The absence of fire has specifically resulted in higher tree densities, reduced spatial heterogeneity, greater proportion of shade-tolerant species (i.e. fire avoiders), increased rates of pathogen-related mortality, and diminished nutrient availability (Arno 1980; Fulé *et al.* 1997; Feeney *et al.* 1998; Allen *et al.* 2002; MacKenzie *et al.* 2004; Stephens and Collins 2004). Alteration of structure and composition of the overstory has directly influenced understory vegetation development and persistence, resulting in reduced understory biomass, cover and diversity in many western pine ecosystems (Abella and Covington 2004; Wienk *et al.* 2004; Wayman and North 2007).

The current state of many ponderosa forests have prompted the use of different fuel treatments to assist in restoration and improved resiliency of these systems (Agee and Skinner 2005). Recent studies have investigated the impact of several fuels treatment methods (e.g., thinning and/or prescribed fire) on understory vegetation response (Griffis *et al.* 2001; Metlen *et al.* 2004; Wienk *et al.* 2004; Metlen and Fiedler 2006; Knapp *et al.* 2007; Wayman and North 2007). Few studies have evaluated the effect of a relatively new fuels treatment, mechanical mastication, on understory vegetation. Previous studies have investigated mechanical mastication within shrub-dominated ecosystems (Bradley *et al.* 2006; Sikes 2006) or as only a portion of the thinning treatment (i.e. use of traditional harvesting in addition to mastication; Collins *et al.* 2007). No published studies have characterized the sole effects of mastication and supplemental treatments on understory vegetation in forested ecosystems.

The primary objective of this study was to evaluate the effect of mechanical mastication and subsequent fuels treatments (e.g. prescribed fire) in comparison to mastication only treatments and untreated controls on understory plant communities. In addition, these fuels treatments were compared to a manual (hand) midstory removal treatment to gain insight into the relative importance of midstory removal alone on understory plant species response in ponderosa pine forests. Specifically, this study aimed to: (1) evaluate the effect of the fuel treatments on environmental variables measured; (2) compare and contrast the response of understory plant species diversity and cover by growth form and functional group to different fuels treatments; (3) evaluate the response of shrub and non-native plant species abundance relative to contrasting fuels treatments; (4) evaluate the relationship between environmental variables and understory vegetation; and (5) determine differences in understory plant communities relative to contrasting fuels treatments.

Methods

Study Site

The study was completed within the Challenge Experimental Forest located on the Plumas National Forest in the northern Sierra Nevada of California (39°29'N, 121°13'W; Fig. 1). The research site resides along predominantly western facing, 0-20% sloping forests at an elevation between 800 and 900 m above sea level. The climate is broadly characterized as Mediterranean due to its hot dry summers and cool wet winters. The mean annual temperature of the Challenge Experimental Forest is 12.3° C. Mean annual precipitation is 1730 mm with 98% falling between October and May as rain (Berg 1990). Any snow accumulations typically melt and rarely form a prolonged snow pack. Soils within the study area are composed of deep, well drained loam to gravelly loam, xeric Haplohumult soils in the Sites series (USDA-NRCS 2007*a*). The study site is located within the lower elevational range of the mixed conifer forest type, however, the dominant overstory species is *Pinus ponderosa*. Additional species include *Pinus lambertiana* (Dougl.), *Pseudotsuga menziesii* (Mirbel) Franco, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr., and *Calocedrus decurrens* (Torr.) Florin and represent < 1% of the total density. Prior to treatment, the dense midstory was composed of hardwood species including *Lithocarpus densiflorus* (Hook. & Arn.) Rehd., *Arbutus menziesii* Pursh, and *Quercus kelloggii* Newberry. The understory was largely dominated by two shrub species: *Ceanothus integerrimus* Hook. & Arn. and *Arctostaphylos viscida* Parry. The land use history of the study area consists of relatively intense logging practices of the past that was typical in the northern Sierra Nevada during the early 1900's

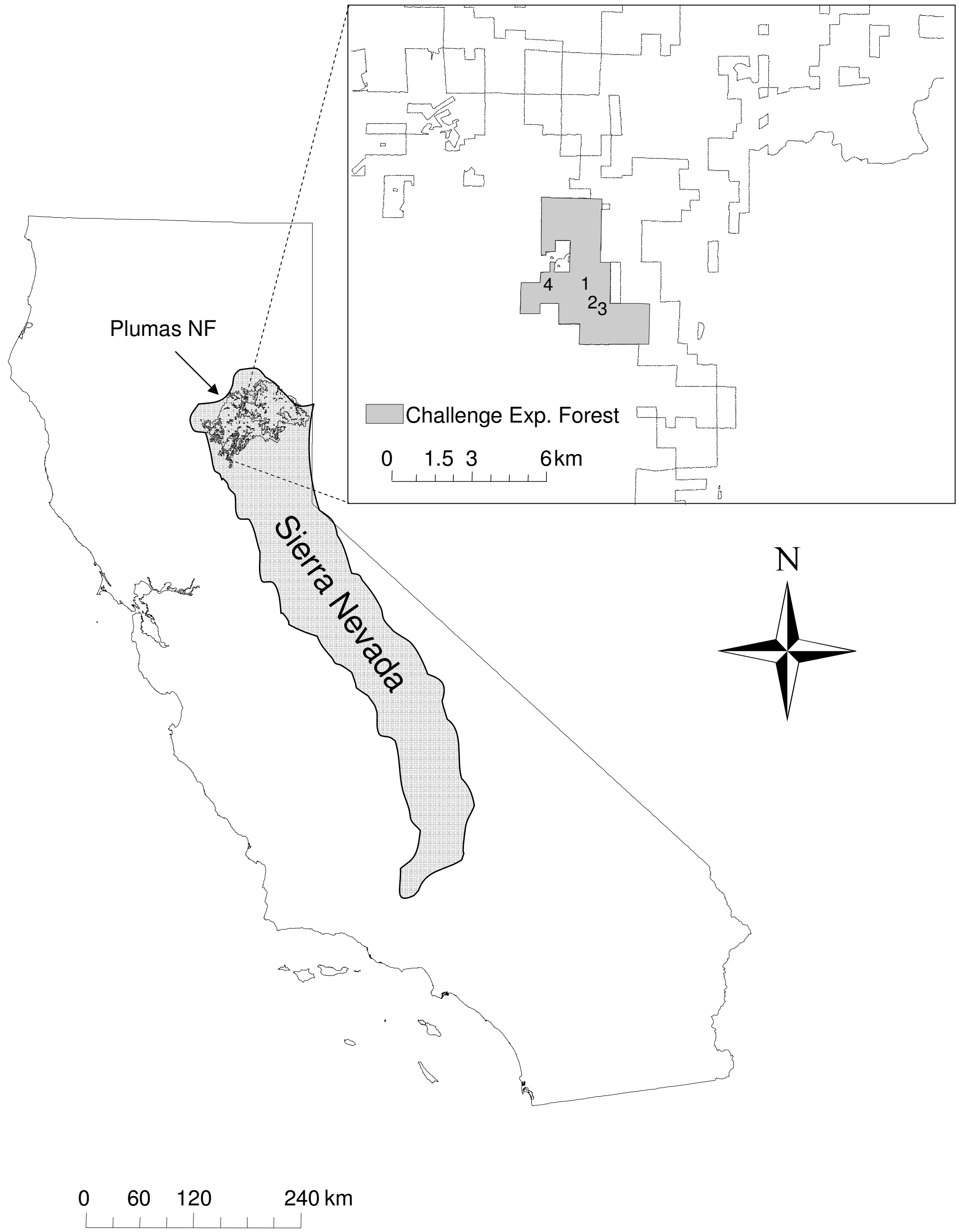

Fig. 1. Location of study area within the Challenge Experimental Forest in the Plumas National Forest, California. Numbers within the Experimental Forest boundary represent the experimental blocks where the study was conducted.

(Berg 1990). The area is currently part of the USDA Forest Service experimental forest system managed and operated by the Pacific Southwest Research Station. Three of the four blocks where this study took place were clear-cut in 1963 and were part of a previous study examining regeneration in various sized openings (McDonald 1983). The other block experienced a wildfire in 1961 and subsequently became a shrub dominant (*A. viscida* and *C. integerrimus*) community type. In the blocks that were clearcut, the slash fuels were broadcast burned and allowed to regenerate naturally, while the block that experienced a wildfire was reclaimed during the "Penny Pines" program, where shrubs were piled and burned, the site planted with *Pinus ponderosa* seedlings, and thinned in the early 1980's. In spite of differing land management histories the blocks contained relatively evenly aged, 40- to 45-years old *P. ponderosa* with similar structural characteristics, having a mean basal area of 29.0 (± 3.2) m^2 ha^{-1} and a mean tree density of 509.6 (± 52.9) stems ha^{-1}.

Treatments

Five fuels treatments were selected for this study, including mastication only (MAST), mastication followed by incorporation (MAST/INC), mastication followed by prescribed burning (MAST/RX), hand removal (HAND), and a no treatment/control (CONTROL). Each treatment was selected based on the practical utility for managers to treat dense second-growth forests to reduce fire hazard. For the MAST and MAST/INC treatments, half of each unit was treated with herbicide as a part of a different study (R. Powers pers. comm.) and these areas were excluded from the vegetation surveys conducted in this study.

All mechanical mastication treatments (MAST, MAST/INC and MAST/RX) were completed in May 2002 with a rotary drum style masticating head with fixed teeth mounted on the front-end of a Rayco® crawler model #T275 (Rayco Manufacturing, Inc., Wooster, OH). Hand removal was also accomplished in May 2002 and involved using chainsaws to cut midstory trees and understory shrubs. The debris was then manually removed from each of the units. The incorporation treatment (MAST/INC) was completed one month after mastication with a 1.8 meter wide rototiller that churned the masticated debris into the upper soil surface (avg. 15 - 25 cm deep). This fuels treatment technique had the management objective of functionally removing some of the surface fuels by burying the wood in the surface mineral soil and thus reducing the availability of fuels to ignite. Incorporation also has the potential to increase decomposition rates of surface fuels due to greater exposure to organisms that decompose the accumulated organic matter.

Prescribed fire treatment units were completed three years after the mechanical mastication treatment. Burning was conducted between 31 May and 28 June 2005. Each unit was ignited by a drip torch and burned with strip head fires from the highest point (upper slope) to the lowest point in the unit with inter-strip distances varying between 5 to 10 m. In some units, backing fires were allowed to progress down slope for longer distances. The weather conditions during each of the four burns had an average temperature of 22-23° C. Average relative humidity ranged from 38-57%. Wind speeds varied between 0.6 to 0.8 m sec^{-1} and were predominately from the southwest. Prescribed fires were conducted with fuel moisture levels of 13%, 13%, 16%, and 58%

for 1-hr, 10-hr, 100-hr, and 1000-hr timelag fuel moisture classes, respectively. As a result, flame lengths of heading fires ranged between 0.5 and 2 m, while backing flame lengths were between 0.1 and 0.9 m.

Experimental Design and Data Collection

The study used a randomized complete block design with four blocks, each containing five 0.4 ha experimental treatment units. Each treatment unit was randomly assigned within each block with the exception of two MAST/RX units which were adjacent for operational ease. All experimental units were surveyed and marked with permanent monuments in the summer of 2001. An array of ten gridpoints marked was systematically spaced throughout each unit (Fig. 2).

After treatments were completed for all units, vegetation was measured in 2006 on one half (five gridpoints) of each experimental unit with the exception of the MAST/RX treatment in which all ten gridpoints were measured. Understory vegetation data were collected in four 1 m x 1 m quadrats along the four cardinal directions, situated one meter away from each gridpoint to minimize impacts of trampling (Fig. 2). Within each of the vegetation quadrats, all vascular plant species were identified following Hickman (1993) and assigned a cover class value (1= <0.25%, 2= 0.25-0.49%, 3= 0.5-0.9%, 4= 1.0-1.9%, 5= 2.0-4.9%, 5= 5.0-9.9%, 6= 10.0-24.9%, 7= 25.0-49.9%, 8= 50-74.9%, 9= 75.0-94.9%, 10= >95%). In addition, all non-native herbaceous species and all shrubs < 50 cm tall were counted in each quadrat. Species richness for each treatment

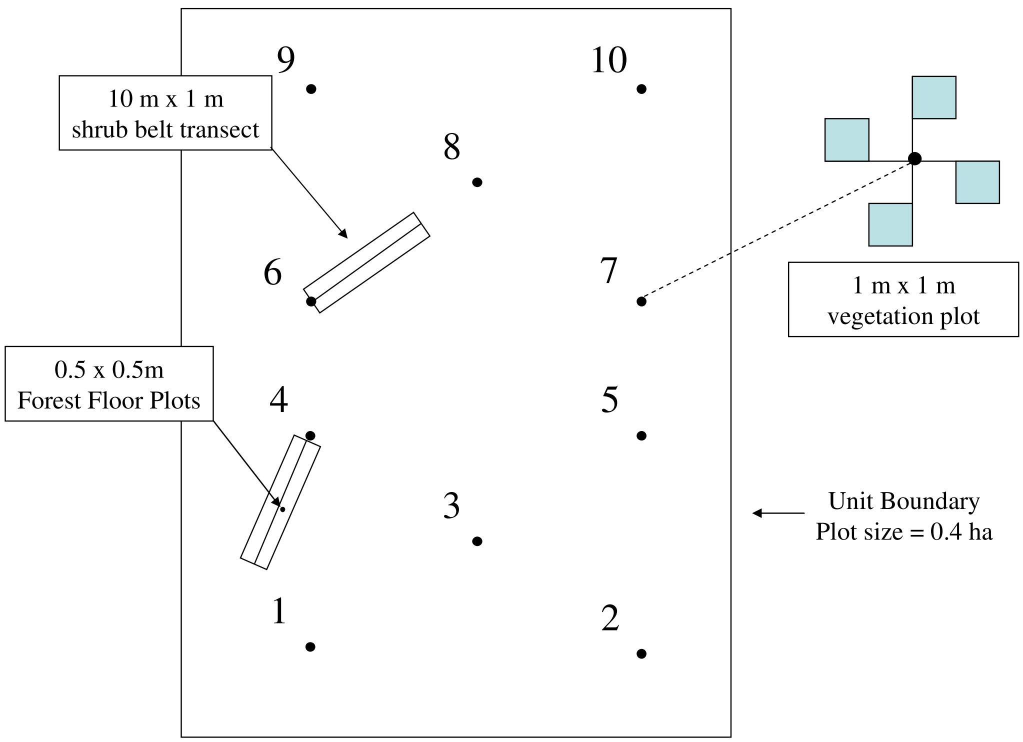

Fig. 2. Vegetation sampling and unit design for fuels treatment study at Challenge Experimental Forest, California.

was calculated by averaging the number of species found within each 1 m^2 quadrat for each of the gridpoints within a treatment unit ($n = 4$). Two diversity indices were calculated for each of the treatment types: Simpson's index of diversity (D) and Shannon diversity index (H′) (Magurran 1988). At each of the gridpoints surveyed, a spherical densiometer (Lemmon 1956) was used to estimate canopy closure.

Understory shrub data were also collected along 10 m by 1 m belt transects placed along a random transect radiating from each gridpoint originating one meter away to minimize trampling effect (Fig. 2). Along each transect, all shrub species > 50 cm tall were tallied. For every fifth shrub, the height was recorded to the nearest 10 cm for each species. Shrub height measurements ceased after five heights were taken for each species and each transect.

In addition to vegetation data, information on surface fuel loading was collected within a 50 cm x 50 cm metal frame placed along a random azimuth, positioned 7 m from the gridpoint. Ground cover (percent woody cover, percent bare ground, and percent litter) for each fuels treatment was estimated by assigning each cover type as the cover class value (previously described), within the fuels sampling frame. In the treatment types where recently fallen litter had masked the cover values associated with the immediate post-treatment groundcover (i.e. MAST, MAST/INC, MAST/RX), the post-treatment fallen litter was manually removed and the cover classes assigned.

To evaluate fuelbed depth, four 25 cm large-gauged nails were pounded in 10 cm diagonally from each of the frame corners with the nail head flush with the surface of the litter and fuelbed depth measured in two distinct layers: litter depth (cm) and duff depth (cm). Litter consisted of recently fallen needles, leaves and woody debris along the surface of the forest floor. The underlying duff was composed of the fermentation horizon and the partially to fully decomposed humus horizon beneath. Each layer was progressively removed from the frame and placed within labeled paper bags. In the event that a woody fuel particle crossed the frame, the piece was cut along the horizon boundary and segregated into respective horizons/layers. All woody fuels were separated by timelag fuel moisture classes from each of their respective layers in the lab, oven-dried for at least 72 hrs at 85º C in a mechanical convection oven, and then weighed on an analytical balance.

Data Analysis

The vegetation response to each of the fuels treatments was evaluated by calculating the mean cover, frequency, species richness, and diversity indices of all species occurring with the 1 m x 1 m quadrats at the unit level for each treatment (n = 5) and all blocks (n = 4). In addition, mean stem density was calculated within each quadrat for all non-native herbs and shrub species < 50 cm tall. For all shrub species < 50 cm tall, average height and density were calculated along each belt transect for each treatment in all blocks (Fig. 2).

Data were analyzed using an ANOVA in NCSS (Hintze 2007) to test for fuels treatment effects on plant variables (cover, diversity, non-native plant density, and shrub density) and environmental variables (midstory height, ground cover, fuel depth and load, and canopy closure). A mixed model ANOVA was completed with treatment as a fixed variable and block as a random variable. When significant treatment effects were found

($\alpha < 0.05$), tests between individual treatments were conducted using the Tukey-Kramer multiple comparison test (Sokal and Rohlf 1995).

To determine potential drivers of plant cover and diversity response to the different fuels treatments a step-wise multiple regression procedure was performed to determine which environmental variables were most strongly associated with differences in species richness. All environmental variables were inspected for violations in the assumptions of a multiple regression analysis. For instance, multicolinearity was suspected if the variance inflation factor value for a variable was > 10 and was subsequently removed from the regression analysis and the analysis performed again. All independent environmental variables found to significantly predict species richness were included in the final model.

Indicator species analyses were performed using PC-ORD version 5.0 (McCune and Mefford 1999) to detect whether individual species were associated with a particular fuels treatment. Both species cover and frequency values were used to calculate indicator values for each species in which each value was averaged at the unit ($n = 4$) and treatment level ($n = 5$). Indicator values range from 0 to 100, where 100 represented a species that has full fidelity to one particular fuels treatment. The *P*-values calculated with this procedure represent the probability of obtaining an indicator value equal to or greater than one obtained by chance. Randomly generated data were computed based on a Monte Carlo test with 5000 randomizations (McCune and Grace 2002).

Assessment of the understory plant community response to the different fuels treatments was conducted using a Bray-Curtis ordination procedure in PC-ORD version

5.0 (McCune and Mefford 1999). A reason for using the Bray-Curtis method of ordination to evaluate the plant community responses to treatments is because the control treatment provides a reference condition or end-point utilized to make comparisons between treatments (McCune and Grace 2002). Within the Bray-Curtis ordination method, Sorensen distance measures and variance-regression endpoint selection were used to generate axes values. An ordination was computed based on using species frequency data averaged to the unit level ($n = 4$) for each fuels treatment. In addition, environmental data associated with the respective treatment sample were overlaid as joint plots to show the variables most responsible ($r^2 \geq 0.2$) for separation of treatment communities in species space.

To detect whether understory plant community composition varied significantly due to fuels treatments, a non-parametric blocked multiple response permutation procedure was calculated based on frequency data. The frequency dataset represents the proportion of times a species was encountered within all 1 m^2 quadrat subsamples for a given unit. Euclidian distances were used to calculate axes values, while groups were assigned based on the fuels treatment performed. For each analysis, a chance-corrected within-group agreement (*A*) value was calculated where *A* is equal to one minus the division between the observed versus the expected weighted mean within-group distance (delta). If $A = 0$, then the heterogeneity within groups is equal to that by chance, while if $A = 1$ (delta = 0), then all items are identical within each respective group. The *P*-value generated from this procedure represents the probability of getting an equal or smaller value of delta by chance (McCune and Grace 2002).

Results

Effect of treatments on environmental variables

Many environmental variables measured within this study varied significantly among the different fuels treatments (Table 1). Midstory height was significantly different across treatment types ($F = 24.71$, df = 4, $P < 0.001$). All active treatments had lower midstory heights than the CONTROL. All fuels treatments resulted in at least a 10% reduction in canopy closure compared to the CONTROL. However, a treatment effect was not significant ($F = 3.10$, df = 4, $P = 0.057$). All measures of ground cover, with the exception of woody debris cover, were significantly affected by treatment (Table 1) with the general characteristics of the CONTROL and HAND treatments which had the least bare ground exposed (< 7 %) and the most litter cover (> 75%). MAST and MAST/INC treatments had high woody cover values (>20%). Mastication treatments followed by supplemental ground disturbances (MAST/INC and MAST/RX) contained significantly greater proportions of bare ground (34% and 43%, respectively) than both CONTROL and HAND treatments (6% and 4%, respectively), which instead had significantly greater proportions of litter cover (Table 1). Litter depth significantly differed by fuels treatment ($F = 3.69$, df = 4, $P = 0.035$), but surprisingly no differences were detected in either litter ($P = 0.072$) or duff ($P = 0.354$) fuel load among treatments.

Effect of treatments on understory plants

Seventy-two vascular plant species were recorded across all fuels treatments including 10

Table 1. Environmental variable means (± SE) for each fuels treatment (CONTROL = no treatment, HAND = hand removal, MAST = mastication only, MAST/INC = mastication and incorporation, MAST/RX = mastication and prescribed fire). The *P*-values represent the results of a mixed model ANOVA and different superscript letters depict significant differences between individual treatment types based on results from Tukey-Kramer multiple comparison tests.

Variable	CONTROL	HAND	MAST	MAST/INC	MAST/RX	*P*-value
Midstory Height (cm)	254.8 (29.0)^{a}	119.7 (7.9)^{b}	120.9 (5.1)^{b}	95.7 (10.8)^{bc}	64.9 (5.2)^{c}	**< 0.001**
Canopy Closure (%)	96.9 (1.2)	85.1 (4.2)	80.4 (3.4)	81.4 (4.7)	71.2 (4.2)	0.057
Bare Ground (%)	6.6 (4.5)^{ab}	3.5 (2.0)^{a}	7.2 (4.6)^{ab}	34.3 (13.9)^{ab}	48.5 (15.8)^{b}	**0.016**
Woody Debris Cover (%)	14.1 (7.8)	2.5 (0.4)	26.4 (5.4)	24.9 (7.9)	9.9 (6.5)	0.097
Litter Cover (%)	78.9 (6.2)^{a}	91.5 (3.6)^{a}	61.9 (6.7)^{ab}	28.0 (7.7)^{c}	31.1 (11.1)^{bc}	**< 0.001**
Litter Depth (cm)	8.1 (1.3)^{ab}	5.9 (0.4)^{b}	7.8 (0.4)^{a}	6.8 (0.5)^{ab}	4.0 (0.3)^{c}	**< 0.001**
Duff Depth (cm)	1.6 (0.4)	1.7 (0.3)	2.0 (0.4)	0.5 (0.2)	1.2 (0.3)	0.337
Litter Load (Mg ha^{-1})	16.4 (4.9)	10.5 (0.9)	19.5 (2.0)	20.6 (4.1)	9.1 (1.9)	0.072
Duff Load (Mg ha^{-1})	10.4 (4.7)	10.3 (2.8)	13.2 (4.2)	5.1 (3.6)	12.5 (3.9)	0.354

trees, 16 shrubs, 7 graminoids, and 38 forbs (Appendix A). Across all life history categories no treatment effect was found for plant cover values (Table 2). A significant treatment effect was detected for the density measures of native shrubs ($P < 0.001$), resprouter ($P < 0.001$), obligate seeder ($P < 0.001$), and non-native forb species ($P = 0.010$) at the 1 m^2 scale (Table 2). The MAST/RX treatment had a greater number of native shrub, resprouter, and obligate seeder stems at the 1 m^2 scale than all other treatments, while MAST/INC had significantly more stems of resprouting species than the CONTROL treatment. Both the MAST and MAST/INC treatments contained greater numbers of non-native forb individuals (0.7 and 0.8 stems per m^2, respectively), when compared to the CONTROL which contained only native forbs (Table 2). At a larger scale (10 m^2) a significant treatment effect was found for native shrub ($F = 5.41$, df = 4, $P = 0.010$) and resprouting shrub densities ($F = 5.94$, df = 4, $P = 0.007$), where both the CONTROL and MAST/RX had fewer native shrubs than the MAST/INC treatment. MAST/RX had significantly fewer resprouting shrubs compared to MAST/INC.

Measures of both species richness and diversity differed across fuels treatments for all categories except graminoid richness and the Shannon diversity index (Table 3). In almost all cases, MAST/RX was the only treatment that was significantly greater in both species richness and Simpson's index of diversity than the CONTROL treatment. For annual/biennial, perennial, forb richness, and the Simpson index of diversity the MAST/INC treatment was significantly greater than the CONTROL treatment (Table 3). Environmental factors modified by fuels treatments significantly related to measures of species richness. Results of a step-wise multiple regression analysis determined that the

Table 2. Understory plant cover and density means (± SE) for each fuels treatment (CONTROL = no treatment, HAND = hand removal, MAST = mastication only, MAST/INC = mastication and incorporation, MAST/RX = mastication and prescribed fire). The *P*-values represent the results of a mixed model ANOVA and different superscript letters depict significant differences between individual treatment types based on results from Tukey- Kramer multiple comparison test.

Variable	CONTROL	HAND	MAST	MAST/INC	MAST/RX	*P*-value
Cover (1 x 1 m)						
All Species	23.8 (10.5)	81.4 (8.9)	54.5 (9.9)	74.4 (24.0)	71.1 (12.3)	0.062
Native	23.5 (10.6)	77.9 (8.9)	46.9 (9.0)	69.6 (25.3)	65.0 (12.3)	0.062
Non-native	0.3 (0.3)	3.4 (2.5)	7.5 (2.6)	4.3 (1.8)	6.0 (3.8)	0.077
Annual/Biennial	0.0 (0.0)	0.1 (0.1)	0.7 (0.6)	0.7 (0.3)	0.6 (0.5)	0.549
Perennial	23.8 (10.5)	81.0 (8.9)	52.9 (8.8)	72.1 (24.0)	69.7 (12.5)	0.062
Forb	14.2 (9.2)	49.7 (5.2)	25.7 (4.2)	42.5 (20.5)	35.3 (15.1)	0.162
Graminoid	0.1 (0.1)	0.1 (0.0)	0.1 (0.0)	0.1 (0.1)	0.0 (0.0)	0.607
Herbaceous	14.3 (9.3)	49.8 (5.2)	25.8 (4.2)	42.6 (20.5)	35.3 (15.1)	0.163
Shrub < 50 cm	8.9 (1.2)	30.8 (7.6)	34.8 (6.7)	31.2 (4.1)	26.9 (13.4)	0.198
Density (1 x 1 m)						
All Shrubs < 50 cm	3.0 (0.9)^{a}	8.8 (1.1)^{a}	4.6 (1.9)^{a}	11.2 (2.4)^{a}	28.1 (3.9)^{b}	**< 0.001**
Native Shrubs < 50 cm	2.9 (0.9)^{a}	8.5 (1.2)^{a}	4.2 (1.8)^{a}	11.0 (2.6)^{a}	27.6 (4.0)^{b}	**< 0.001**
Non-native Shrubs < 50 cm	0.1 (0.0)	0.3 (0.2)	0.4 (0.2)	0.2 (0.1)	0.5 (0.4)	0.488
Resprouters	3.0 (0.9)^{a}	8.0 (1.4)^{ab}	4.7 (1.9)^{ab}	9.4 (2.2)^{b}	26.7 (3.5)^{c}	**< 0.001**
Obligate Seeders	0.0 (0.0)^{a}	0.2 (0.2)^{a}	0.2 (0.1)^{a}	2.1 (0.7)^{a}	17.0 (4.2)^{b}	**< 0.001**
Non-native Forbs	0.0 (0.0)^{a}	0.1 (0.0)^{ab}	0.8 (0.3)^{b}	0.7 (0.4)^{b}	0.4 (0.1)^{ab}	**0.010**
Density (10 x 1 m) > 50 cm						
All Shrubs	245.5 (78.4)	308.5 (54.9)	553.5 (132.5)	564.0 (96.4)	195.0 (53.8)	0.099
Native Shrubs	92.3 (24.9)^{b}	210.3 (36.1)^{ab}	272.0 (58.9)^{ab}	471.5 (90.2)^{a}	272.0 (58.9)^{b}	**0.010**
Non-native Shrubs	153.3 (58.1)	98.3 (38.1)	281.5 (122.3)	92.5 (34.9)	58.0 (31.7)	0.546
Resprouters	285.0 (73.4)^{bc}	383.3 (51.6)^{abc}	606.8 (135.7)^{a}	712.5 (101.2)^{ab}	239.0 (58.4)^{c}	**0.007**
Obligate Seeders	11.3 (9.0)	11.0 (9.8)	3.7 (2.1)	6.4 (3.5)	0.9 (0.9)	0.433

Table 3. Understory species richness and diversity index means (± SE) for each fuels treatment (CONTROL = no treatment, HAND = hand removal, MAST = mastication only, MAST/INC = mastication and incorporation, MAST/RX = mastication and prescribed fire). The *P*-values represent the results of a mixed-model ANOVA (df = 3) and different superscript letters depict significant differences between individual treatment types based on results from Tukey-Kramer multiple comparison test.

Variable	CONTROL	HAND	MAST	MAST/INC	MAST/RX	*P*-value
Richness (# species m^{-2})						
All species	4.3 (1.5)[a]	7.2 (1.0)[ab]	7.4 (0.4)[ab]	9.9 (1.8)[ab]	11.3 (0.8)[b]	**0.002**
Native	4.0 (1.4)[a]	6.6 (0.9)[abc]	6.2 (0.1)[ab]	8.6 (1.8)[bc]	10.0 (0.9)[c]	**0.001**
Non-native	0.2 (0.1)[a]	0.4 (0.1)[ab]	0.8 (0.3)[ab]	0.9 (0.1)[ab]	1.0 (0.5)[b]	**0.044**
Annual/Biennial	0.1 (0.1)[a]	0.1 (0.1)[a]	0.4 (0.2)[ab]	0.9 (0.3)[b]	0.9 (0.2)[b]	**0.009**
Perennial	4.2 (1.4)[a]	6.7 (0.7)[ab]	6.7 (0.4)[ab]	8.3 (1.7)[b]	9.9 (1.0)[b]	**0.007**
Forb	1.8 (1.0)[a]	3.7 (0.7)[ab]	3.9 (0.5)[ab]	4.5 (1.0)[b]	5.2 (0.8)[b]	**0.009**
Graminoid	0.2 (0.2)	0.2 (0.1)	0.2 (0.1)	0.5 (0.2)	0.2 (0.1)	0.194
Herbaceous	1.9 (1.2)[a]	3.9 (0.7)[ab]	4.1 (0.6)[ab]	5.1 (1.2)[b]	5.4 (0.8)[b]	**0.010**
Shrub < 50cm tall	2.0 (0.4)[a]	2.9 (0.2)[a]	2.6 (0.5)[a]	4.2 (0.6)[ab]	5.7 (0.4)[b]	**0.001**
Diversity Indices						
Simpson's Index of Diversity (D)	0.3 (0.1)[a]	0.4 (0.1)[ab]	0.4 (0.0)[ab]	0.5 (0.1)[b]	0.5 (0.0)[b]	**0.020**
Shannon Diversity Index (H′)	0.1 (0.0)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)	0.2 (0.1)	0.409

variables shrub height, canopy closure, and bare ground significantly predicted species richness ($R^2 = 0.33$, $F = 13.8$, $P < 0.001$) in the model: 14.86 + 0.04 * Bare Ground (%) – 0.07 * Canopy Closure (%) – 0.02 * Shrub Ht. (cm) = Species Richness (#/m^2).

Assessment of individual species response to different fuels treatments was conducted with an indicator species analysis that identified plant species significantly associated with a particular treatment group. Most of the individual species cover and frequency values were significantly associated with either the MAST/INC or MAST/RX treatment types (Table 4). For instance, two shrub species (*Arctostaphylos viscida* and *Ceanothus integerrimus*) cover- and frequency-derived indicator values were significantly associated ($P < 0.05$) with both MAST/INC and MAST/RX. Two non-native forbs were also associated to particular treatment type: *Hypericum perforatum*, a perennial, was associated with the MAST treatment while *Lactuca serriola*, an annual, had a high fidelity to the MAST/RX treatment (Table 4).

Plant community response to fuels treatments

The Bray-Curtis ordination of frequency-derived plant community data differed remarkably from the cover-derived analysis. Axis 1 explained 40.7% of the variation while Axis 2 explained 29.4%. Environmental variables that were significantly associated with the ordination gradients were percent bare ground, canopy closure, and litter cover (Fig. 3). For the most part, fuels treatments were situated along a gradient with CONTROL and HAND treatments occupying the area with greatest canopy closure and litter cover. MAST/INC and MAST/RX were located on the other side of the

Table 4. Indicator species analysis of cover and frequency values averaged at the block level ($n = 4$) for individual species associated with a particular fuels treatment type. Indicator values (I.V.) range from 0 to 100, where 100 represents complete fidelity to a particular treatment. The P-values represent the probability of obtaining an IV as large or larger by chance, an asterisk denotes significance at $\alpha < 0.05$. Computation is based on a Monte Carlo test with 5000 randomizations.

	Cover			Frequency		
Species	Treatment	I.V.	*P-value*	Treatment	I.V.	*P-value*
Arctostaphylos viscida	MAST/INC	66.2	0.008*	MAST/RX	52.0	0.032*
Aster oregoniensis	MAST/RX	43.1	0.187	MAST/INC	45.7	0.074
Ceanothus integerrimus	MAST/INC	53.0	0.048*	MAST/RX	53.5	0.001*
Cirsium vulgare	MAST/INC	32.0	0.426	MAST/INC	46.3	0.053
Gnaphalium canescens	MAST/INC	48.6	0.112	MAST/INC	62.1	0.018*
Hypericum perforatum	MAST	58.6	0.044*	MAST	42.0	0.233
Lactuca serriola	MAST/RX	75.0	0.019*	MAST/RX	75.0	0.020*
Lathrys sulfurous	MAST/INC	70.4	0.027*	MAST/INC	53.6	0.047*
Lotus sp.	MAST/RX	60.0	0.038*	MAST/RX	56.2	0.051
Ribes roezlii	HAND	33.0	0.567	MAST/RX	58.6	0.023*
Toxicodendron diversilobum	MAST/RX	33.6	0.109	MAST/RX	26.7	0.049*
Vicia sp.	MAST/RX	100.0	0.001*	MAST/RX	100.0	0.002*

ordination associated with greater canopy openness and greater proportion of bare ground (Fig. 3). A significant treatment effect on plant community frequency data was revealed based on the results of a blocked multiple response permutation procedure (A = 0.58, $P < 0.001$). All treatment types were significantly different from one another ($P <$ 0.030).

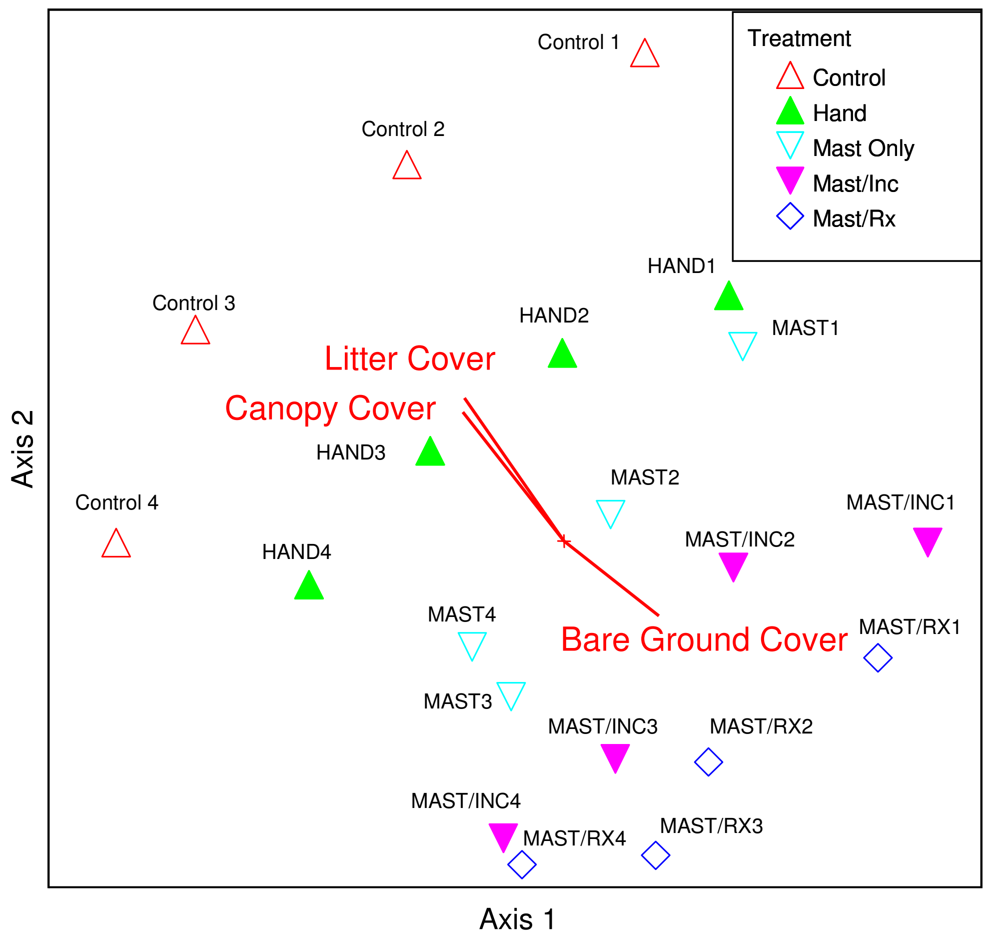

Fig. 3. Plant community analysis results using frequency values for each treatment unit. Positional results were calculated using the Bray-Curtis ordination method. Axis 1 explained 40.7% of the variation while Axis 2 explained 29.4% of the variation. Significant environmental variables ($r^2 \geq 0.2$) are represented by the join plots.

Discussion

Mechanical mastication is primarily concerned with reducing fire hazard through the reduction of midstory fuel heights (Kane *et al.* 2006). While fuel hazard reduction is important, many managers are additionally concerned with the impact of mechanical mastication on the structure, composition, and function of these ecosystems. The feasibility of mechanical mastication as a restoration tool is contingent upon the efficacy of this fuels treatment to reduce fire hazard and high severity wildfires. Some studies have shown evidence for undesirable fire effects from reintroduction of prescribed fire following mastication (Bradley *et al.* 2006, Knapp *et al.* 2006). Continued research that evaluates effectiveness of mastication as a fuels hazard reduction technique is needed.

None of the fuels treatments implemented in this study significantly altered the cover for any of the different plant life forms found in the understory (Table 2). Lack of a significant plant cover change compared to the control, while somewhat surprising, has been found in other studies investigating fuels treatments (Wienk *et al.* 2004; Metlen and Fiedler 2006). Understory plants are relatively resilient to disturbances, especially those in fire-prone forests and a rapid response of plant growth was not completely unexpected. This resilience is most likely due to the preponderance of perennial plant species that are resistant to change in the short term and often resprout after disturbances. Since fuels treatments in this study were not implemented at the same time, differences in rate of vegetative response may have differed among treatments. For example, vegetation sampling occurred four years after the treatment for the HAND, MAST, and MAST/INC treatments but only one year after the MAST/RX treatment was completed. A lack of a significant difference between these treatments suggests that the rate of recovery in the MAST/RX may be faster or that a majority of the vegetation response occurred within the first year or two. Additionally, understory vegetation measures within this study were only conducted at the 1 m^2 scale and other trends may exist at larger scales for both cover and diversity measures as exemplified by other studies (Schwilk *et al.* 1997; Metlen and Fiedler 2006; Knapp *et al.* 2007).

Midstory height was significantly reduced in all treatments compared to the control (Table 1). However, canopy closure did not differ significantly by treatment. The lack of a significant treatment effect on canopy closure may be due to the fact that mastication treatments predominately treated the midstory layer. It is equally if not more likely that the coarseness of the spherical densiometer estimates may have failed to detect a difference between treatments (Engelbrecht and Herz 2001). Reductions in canopy closure and midstory heights would presumably increase the amount of solar radiation penetrating the canopy and available to understory plants. While the treatment effects on both canopy closure and midstory height were mixed, both surrogate measures of light conditions (midstory height and canopy closure) were found to be negatively correlated with species richness and diversity (Appendix B). Other studies have demonstrated the importance of solar radiation on plant species richness (Pausas and Austin 2001; North *et al.* 2005). However, other environmental variables, such as soil moisture (Wayman and North 2007) and nutrient heterogeneity (Gundale 2006) have shown to be more better related to higher plant diversity.

Measures of ground cover including bare ground, litter cover, and litter depth were significantly altered by fuels treatments (Table 1). Bare ground was positively correlated with species richness throughout all fuels treatments (Appendix B). Greater proportions of bare ground were associated with both the MAST/INC and MAST/RX treatments. In the MAST/INC treatment, bare ground increased as the result of the tilling process which churned and exposed mineral soil to the surface of the forest floor. Bare ground in the MAST/RX treatments was the result of burning of the forest floor. Increases in the amount of bare ground allow for greater recruitment and establishment of individual plant species by reducing competition and increasing the available growing space. Species that require exposed mineral soil for germination further increase the likelihood of establishment in these conditions. While both MAST/INC and MAST/RX provided greater exposed mineral soil, both treatments also caused ground disturbances that may promote germination through physical scarification or chemical cues. The tilling process in the MAST/INC treatment may scarify seeds by churning the surface with the machinery, while the MAST/RX treatment may promote germination through chemical cues such as heat-shocked (Keeley and Bond 1997) or smoke-triggered germination (Keeley and Fotheringham 1976). In addition to the presence of bare ground, the patchiness or heterogeneity of resources is also likely to influence plant diversity measures. The prescribed burning treatment was conducted early in the growing season under relatively moist and cool conditions. This may have created more patchiness in the consumption of ground fuels contributing to greater levels of understory diversity than burning under drier prescribed burning conditions or under wildfire conditions.

Fuels treatments with supplemental ground disturbances generally had lower proportions of litter cover and reduced litter depths. Both litter cover and litter depth were negatively correlated with species richness throughout all treatment units. CONTROL, HAND and MAST treatments generally had higher litter cover and depth values. The presence of litter seemingly prohibits germination of many species and thus is associated with reductions in species richness and diversity (Sydes and Grime 1981; Xiong and Nillson 1999; Pausas and Austin 2001). Other studies have also found a relationship between ground cover and species diversity measures as a result of mechanical treatments (Battles *et al.* 2001; Newmaster *et al.* 2007) and prescribed fire (Sparks *et al.* 1998; Knapp *et al.* 2007).

The addition of organic material resulting from the MAST treatment units did not apparently contribute to a reduction in species richness compared to either the CONTROL or HAND treatments. Potential reductions in species richness in the MAST plots due to ground cover additions may have been offset by ground disturbance caused by the use of the mastication equipment which often churned some of the mineral soil as the machinery passed repeatedly across the forest floor. It is also possible that there is a non-linear relationship between forest floor depth and species richness. In this case, increases in forest floor depth are not proportional to decreases in species richness. Non-linear responses of species richness to environmental variables have been demonstrated in other forest types (Pausas and Austin 2001).

The relative importance of ground disturbance versus midstory removal in restoring understory plant communities is not well understood in ponderosa pine forest types. However, many suggest that the exclusive removal of the midstory trees and shrubs or reintroduction of fire alone is insufficient (Griffis *et al.* 2001, Fulé *et al.* 2002; Collins *et al.* 2007). In these studies the authors stated that increases in understory plant species diversity required both the opening of the canopy (provided by thinning) as well as removal of the litter layer (provided by prescribed burning). A recent study looking at the relative importance of ground disturbance and midstory removal in *Pinus palustris* forests suggested that removal of the litter and duff horizons was proportionally more important than removal/mortality of the midstory in promoting understory plant cover and diversity (Hiers *et al.* 2007). Results of this study suggest that removal of the midstory alone does not amply restore the species richness of the understory without a supplementary ground disturbance treatment (e.g., incorporation or prescribed fire). Future work is needed to better understand the relative importance of both midstory/overstory removal and ground disturbances and their relative importance for restoring/promoting understory diversity.

The response of shrub species varied significantly among fuels treatment, with shrub stems < 50 cm tall at the small scale (1 m^2) having much higher obligate seeder densities in the MAST/RX than all other treatments (Table 2). In addition, resprouter shrub densities were significantly greater in the MAST/RX and MAST/INC treatment types. This response is due to the presence of two specific shrub species: *Ceanothus integerrimus* and *Arctostaphylos viscida*. Both shrubs are obligate seeders that germinate as the result of fire. Periods of fire exclusion have thus allowed for the storage of these obligate seeder species in the soil seed bank (Quick 1956) and resulted in prolific germination and establishment after fire. The response of obligate seeding and resprouting shrub species is a fire management concern because proliferation of understory shrubs may reduce the longevity and effectiveness of the fuels treatment. Additional treatments may be required to maintain fuel hazard reductions in these forests depending on rates of survival of the shrub species.

A major concern in restoring fire-prone forested systems with mechanical treatments and/or with prescribed fire is the development and spread of non-native plant species (Keeley 2006). Mechanical only treatments (MAST and MAST/INC) resulted in significantly greater non-native forb density than the control (Table 2) and MAST/RX resulted in a greater number of non-native species (Table 1). These results are similar to the findings of others that suggest that as disturbance intensity increases, abundance and richness of non-native plants increases (Griffis *et al.* 2001; Wienk *et al.* 2004; Dodson and Fiedler 2006). Since the prescribed fire treatment was only implemented one year prior to sampling, abundance levels in the MAST/RX units may continue to increase and approach the MAST and MAST/INC fuels treatment densities. Whether the proliferation of non-native species is only a temporary concern in restoration of ponderosa pine forests or if their presence and persistence will influence ecosystem function over the long term is not well understood.

The impacts of fuels treatments on understory plant communities resulted in a significant shift community structure (Fig. 3). Based on plant community analysis, the species composition shifted along environmental gradients altered by the fuels treatments. The frequency of species associated with increased bare ground, reduced litter cover and lower canopy closure. These characteristics were most commonly found in the MAST/INC and MAST/RX treatments. While the plant community composition was significantly affected by the treatments implemented, the shift in composition seemed to occur along a disturbance intensity gradient where MAST/RX resulted in the most extreme difference (Fig. 3). This result suggests that the shift in community structure from the CONTROL treatment may represent an understory plant community more emblematic of pre-suppression conditions. However, reference conditions for northern sierra ponderosa pine forests are not available and more research is necessary. There are few studies investigating the impact of mastication on plant communities. Sikes (2006) investigated the impact of mastication on southern Oregon chaparral shrub communities and found no significant community alteration. However, Wolk (2007) detected a significant shift in plant community structure within chipped ponderosa pine forests in the Front Range of Colorado (Wolk 2007).

Overall, the process of mastication may be well-suited for restoring understory plant communities and richness in second-growth ponderosa pine forests containing a dense midstory layer of small trees and shrubs by increasing canopy openness and allowing for the reintroduction of prescribed burning. Use of prescribed burning can further reduce fuel loading and increase the proportion of exposed mineral soil, both of which are important for understory plant species establishment. While the use of mastication and incorporation seemed to simulate the ground disturbance provided by the prescribed fire, species richness levels were lower than MAST/RX and the abundance of non-native species was higher. Conversely, the use of prescribed fire increases the density of shrub species and without subsequent treatments may reduce the longevity of the fuels treatment.

In general, implementation of mastication as a restorative tool may be appropriate for second-growth ponderosa pine forests. Reference conditions to guide restoration of understory plant communities in ponderosa pine forests of the northern Sierra-Nevada are nonexistent. However, restoring the structure and ecosystem functions, which can be discerned from fire history studies (Moody *et al.* 2006), should positively contribute to the restoration of these ecosystems. A potentially more important issue than restoration is the use of mastication to improve the ecosystem's resiliency to catastrophic wildfires that may result from not treating these forests. The use of mastication to promote greater resiliency should also consider the life history of the species being masticated. For instance, resprouting shrub species may compromise the longevity of the fuels treatment by reestablishing the midstory and increasing the vertical continuity of the forest. On the other hand, the mastication of shrub species that are obligate seeders may suppress shrub regeneration by establishing a mulch layer that inhibits germination.

The use of mechanical mastication should be contextual to the goals of the project and its location. These goals should consider the impacts of mastication from both a fuels management and ecological perspective. Mastication is one of many management options, some of which may be more suitable to aid in promoting resilient forests. One of the obvious benefits of using mastication is that it allows for subsequent reintroduction of prescribed fire to dense second-growth forests that may otherwise experience a more uncharacteristically severe wildfire. In addition, strategic implementation of mastication along fuelbreaks and the wildland urban interface may contribute to protecting and more importantly treating adjacent forests in similar conditions. As the use of mechanical mastication continues, future work is necessary to help inform managers as to the positive and negative impacts of mastication. Studies that look at more long term effects of mastication on understory plant species are needed. While specific studies investigating the influence of season (dormant vs. growing season) and intensity (duration or height of remaining stem) of mastication on vegetation response may further increase the utility of mastication as a resource management tool.

References

Abella SR, Covington WW (2004) Monitoring an Arizona ponderosa pine restoration: sampling efficiency and multivariate analysis of understory vegetation. *Restoration Ecology* **12**, 359-367.

Agee JK, Skinner C (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83-96.

Allen CD, Savage M, Falk DA, Suckling KF, Swetnam TW, Schulke T, Stacey PB, Morgan P, Hoffman M, Klingel JT (2002) Ecological restoration of Southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications* **12**, 1418-1433.

Arno SF (1980) Forest fire history in the northern Rockies. *Journal of Forestry* **78**, 460-465.

Battles J, Shlisky A, Barrett R, Heald R, Allen-Diaz B (2001) The effects of forest management on plant species diversity in a Sierran conifer forest. *Forest Ecology and Management* **146**, 211-222.

Berg NH (1990) Experimental forests and ranges: Field research facilities of the Pacific Southwest Research Station. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-119. (Berkeley, CA)

Bradley T, Gibson J, Bunn W (2006) Fuels management and non-native plant species: an evaluation of fire and fire surrogate treatments in a chaparral plant community. Final Report to the Joint Fire Science Program. Available at http://www.firescience.gov/projects/01B-3-3-27/01B-3-3-27_final_report.pdf.

Collins BM, Moghaddas JJ, Stephens SL (2007) Initial changes in forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* **239**, 102-111.

Dodson EK, Fiedler CE (2006) Impacts of restoration treatments on alien plant invasion in *Pinus ponderosa* forests, Montana, USA. *Journal of Applied Ecology* **43**, 887-897.

Engelbrecht BMJ, Herz HM (2001) Evaluation of different methods to estimate understorey light conditions in tropical forests. *Journal of Tropical Ecology* **17**, 207-224.

Feeney SR, Kolb TE, Covington WW, Wagner MR (1998) Influence of thinning and burning restoration treatments on presettlement ponderosa pines at the Gus Pearson Natural Area. *Canadian Journal of Forest Research* **28**, 1295-1306.

Fulé PZ, Covington WW, Moore MM (1997) Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* **7**, 895-908.

Fulé PZ, Covington WW, Smith HB, Springer JD, Heinlein TA, Huisinga KD, Moore MM (2002) Comparing ecological restoration alternatives: Grand Canyon, Arizona. *Forest Ecology and Management* **170**, 19-41.

Griffis KL, Crawford JA, Wagner MR, Moir WH (2001) Understory response to management treatments in northern ponderosa pine forests. *Forest Ecology and Management* **146**, 239-245.

Gundale MJ, Metlen KL, Fiedler CE, DeLuca TH (2006) Nitrogen spatial heterogeneity influences diversity following restoration in a ponderosa pine forest, Montana. *Ecological Applications* **16**, 479-489.

Hickman JC (1993) 'The Jepson manual: higher plants of California'. (University of California Press: Berkeley, CA)

Hiers JK, O'Brien JJ, Will RE, Mitchell RJ (2007) Forest floor depth mediates understory vigor in xeric *Pinus palustris* ecosystems. *Ecological Applications* **17**, 806-814.

Hintze JL (2007) Number Crunching Statistical Systems (NCSS), Version 2007. (Kaysville, UT)

Kane JM, Knapp EE, Varner JM (2006) Variability in loading of mechanically masticated fuelbeds in northern California and southwestern Oregon. In: Fuels management—How to measure success: Conference Proceedings, (compilers PL Andrews, BW Butler), USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41. pp. 341-350. (Fort Collins, CO)

Keeley JE (2006) Fire management impacts on invasive plants in the western United States. *Conservation Biology* **20**, 375-384.

Keeley JE, Bond WJ (1997) Convergent seed germination in South African fynbos and California chaparral. *Plant Ecology* **133**, 153-167.

Keeley JE, Fotheringham CJ (1976) Trace gas emissions and smoke-induced seed germination. *Science* **276**, 1248-1250.

Knapp EE, Busse MD, Varner JM, Skinner CN, Powers RF (2006) Behavior and short-term effects of fire in masticated fuelbeds. In ‘Proceedings of the Third International Fire Ecology and Management Congress’. Nov. 13-17, San Diego, CA. Available at http://www.fs.fed.us/psw/programs/ecology_of_western_forests/publications/publications/Knapp_AFE2006.pdf [verified 23 Oct 2007]

Knapp EE, Schwilk DW, Kane JM, Keeley JE (2007) Role of burning season on initial understory vegetation response to prescribed burning in a mixed conifer forest. *Canadian Journal of Forest Research* **37**, 11-22.

Lemmon RE (1956) A spherical densiometer for estimating forest overstory density. *Forest Science* **2**, 314-320.

MacKenzie DM, DeLuca TH, Sala A (2004) Forest structure and organic matter analysis along a fire chronosequence in the low elevation forests of western Montana. *Forest Ecology and Management* **203**, 331–343.

Magurran AE (1988) ‘Ecological Diversity and its Measurement’. (Chapman and Hall: London)

McCune B, Grace JB (2002) Analysis of Ecological Communities. MjM Software. (Gleneden Beach, OR)

McCune B, Mefford MJ (1999) PC-ORD. Multivariate Analysis of Ecological Data. Version 5.0. MjM Software. (Gleneden Beach, OR)

McDonald PM (1983) Clearcutting and natural regeneration. Management implications for the Northern Sierra Nevada. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-70. (Berkeley, CA)

Metlen KL, Fiedler CE (2006) Restoration treatment effects on the understory of ponderosa pine/Douglas-fir forests in western Montana, USA. *Forest Ecology and Management* **222**, 355-369.

Metlen KL, Fiedler CE, Youngblood A (2004) Understory response to fuel reduction treatments in the Blue Mountains of northeastern Oregon. *Northwest Science* **78**, 175–185.

Moody TJ, Fites-Kaufman J, Stephens SL (2006) Fire history and climate influence from forests in the northern Sierra Nevada, USA. *Fire Ecology* **2**, 115-141.

North M, Oakley B, Fiegener R, Gray A, Barbour M (2005) Influence of light and soil moisture on the Sierran mixed-conifer understory community. *Plant Ecology* **177**, 13–24.

Newmaster SG, Parker WC, Bell FW, Paterson JM (2007) Effects of forest floor disturbances by mechanical site preparation on floristic diversity in a central Ontario clearcut. *Forest Ecology and Management* **246**, 196-207.

Pausas JG, Austin MP (2001) Patterns of plant species richness in relation to different environments: An appraisal. *Journal of Vegetation Science* **12**, 153-166.

Quick CR (1956) Viable seeds from the duff and soil in sugar pine forests. *Forest Science* **2**, 36-42.

Schwilk DW, Keeley JE, Bond WJ (1997) The intermediate disturbance hypothesis does not explain fire and diversity patterns in fynbos. *Plant Ecology* **132**, 77-84.

Sokal RR, Rohlf FJ (1995) 'Biometry: The principles and practice of statistics in biological research'. 3rd edition. (W. H. Freeman and Co: New York, NY)

Sikes KG (2006) Effects of two fuel reduction treatments on chaparral communities in southwest Oregon. Thesis. Oregon State University. (Corvalis, OR)

Sparks JC, Masters RE, Engle DM, Palmer MW, Bukenhofer GA (1998) Effects of late growing season and late dormant season prescribed fire on herbaceous vegetation in restored pine-grassland communities. *Journal of Vegetation Science* **9**, 133-142.

Stephens SL, Collins BM (2004) Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. *Northwest Science* **78**, 12-23.

Sydes C, Grimes JP (1981) Effects of tree litter on herbaceous vegetation in deciduous woodlands II: an experimental investigation. *Journal of Ecology* **69**: 249-262.

USDA-NRCS, 2007*a*. Web Soil Survey, Version 2.0. USDA, Natural Resource Conservation Service. Available at http://www.websoilsurvey.nrcs.usda.gov/ [Accessed 10 September 2007]

USDA-NRCS, 2007*b*. The PLANTS database. National Plant Data Center, Baton Rouge, LA. Available at http://www. plants.usda.gov [Accessed 4 September 2007].

Wayman RB, North M (2007) Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. *Forest Ecology and Management* **239**, 32-44.

Wienk CL, Sieg CH, McPherson GR (2004) Evaluating the role of cutting treatments, fire and soil seed banks in an experimental framework in ponderosa pine forests of the Black Hills, South Dakota. *Forest Ecology and Management* **192**, 375-393.

Wolk B (2007) Effects of thinning and chipping on tree regeneration and understory plant communities in a ponderosa pine forest, Boulder County, Colorado. Thesis. Colorado State University. (Fort Collins, CO)

Xiong S, Nilsson C (1999) The effects of plant litter on vegetation: a meta-analysis. *Journal of Ecology* **87**, 984-994.

Appendix A: Species list and life history information for all vascular plants occurring within the study site at the Challenge Experimental Forest. Nomenclature follows Hickman (1993) and the species codes were derived from the PLANTS database (USDA-NRCS 2007b).

Species Code	Family	Genus	Species	Growth form	Lifespan	Origin
ABCO	Pinaceae	*Abies*	*concolor*	Tree	Perennial	Native
ACLE8	Poaceae	*Achnatherum*	*lemmoniii*	Graminoid	Perennial	Native
ACMA3	Aceraceae	*Acer*	*macrophyllum*	Tree	Perennial	Native
APAN2	Apocynaceae	*Apocynum*	*androsaemifolium*	Forb	Perennial	Native
ARME	Ericaceae	*Arbutus*	*menziesii*	Tree	Perennial	Native
ARVI4	Ericaceae	*Arctostaphylos*	*Viscida*	Shrub	Perennial	Native
ASOR	Asteraceae	*Aster*	*oregoniensis*	Forb	Perennial	Native
BRCA5	Poaceae	*Bromus*	*carinatus*	Graminoid	Perennial	Native
CADE27	Cupressaceae	*Calocedrus*	*decurrens*	Tree	Perennial	Native
CALYS	Convolvulaceae	*Calystegia*	*sp.*	Forb	Perennial	Native
CAPR15	Campanulaceae	*Campanula*	*prenanthoides*	Forb	Perennial	Native
CAREX	Cyperaceae	*Carex*	*sp.*	Graminoid	Unknown	Native
CEIN	Rhamnaceae	*Ceanothus*	*integerrimus*	Shrub	Perennial	Native
CEPR	Rhamnaceae	*Ceanothus*	*prostratus*	Shrub	Perennial	Native
CHFO	Rosaceae	*Chamaebatia*	*foliolosa*	Shrub	Perennial	Native
CHPO3	Liliaceae	*Chlorogalum*	*pomeridianum*	Forb	Perennial	Native
CHRYS9	Asteraceae	*Chrysothamnus*	*sp.*	Shrub	Perennial	Native
CIVU	Asteraceae	*Cirsium*	*Vulgare*	Forb	Biennial	Alien
CLAYT	Portulaceae	*Claytonia*	*sp.*	Forb	Annual	Native
CLRH	Onagraceae	*Clarkia*	*rhomboidea*	Forb	Annual	Native
COHE2	Polemoniaceae	*Collomia*	*heterophylla*	Forb	Annual	Native
CONU4	Cornaceae	*Cornus*	*Nuttallii*	Tree	Perennial	Native
DEEL	Poaceae	*Deschampsia*	*elongata*	Graminoid	Perennial	Native
DIFO	Fumariaceae	*Dicentra*	*formosa*	Forb	Perennial	Native
DIHO3	Liliaceace	*Disporum*	*Hookeri*	Forb	Perennial	Native

Appendix A (cont.): Species list and life history information for all vascular plants occurring within the study site at the Challenge Experimental Forest. Nomenclature follows Hickman (1993) and the species codes were derived from the PLANTS database (USDA-NRCS 2007*b*).

Species Code	Family	Genus	Species	Growth form	Lifespan	Origin
ELGL	Poaceae	Elymus	Glaucus	Graminoid	Perennial	Native
EPILO	Onagraceae	Epilobium	spp.	Forb	Unknown	Native
ERLAG	Asteraceae	Eriophyllum	lanatum var. grandiflorum	Forb	Perennial	Native
FESTU	Poaceae	Festuca	spp.	Forb	Unknown	Native
FRCA6	Sterculiaceae	Fremontodendron	californicum	Shrub	Perennial	Native
FRVE	Rosaceae	Fragaria	Vesca	Forb	Perennial	Native
GAAP2	Rubiaceae	Galium	Aparine	Forb	Annual	Native
GALIU	Rubiaceae	Galium	Sp	Forb	Unknown	Unknown
GNCA2	Asteraceae	Gnaphalium	canescens	Forb	Unknown	Native
HYPE	Hypericaceae	Hypericum	perforatum	Forb	Perennial	Alien
HYPOC4	Asteraceae	Hypochoeris	sp.	Forb	Unknown	Alien
IRIS	Iridaceae	Iris	sp.	Forb	Perennial	Native
LASE	Asteraceae	Lactuca	Serriola	Forb	Annual	Alien
LASU	Fabaceae	Lathyrus	Sulfurous	Forb	Perennial	Native
LIDE3	Fagaceae	Lithocarpus	densiflorus	Tree	Perennial	Native
LOHIV	Caprifoliaceae	Lonicera	Hispidula var. vacillans	Shrub	Perennial	Native
LOTUS	Fabaceae	Lotus	sp.	Forb		Native
LUPIN	Fabaceae	Lupinus	sp.	Forb	Perennial	Native
MAGR3	Asteraceae	Madia	Gracilis	Forb	Annual	Native
MEHA2	Poaceae	Melica	Harfordii	Graminoid	Perennial	Native
MITO	Scrophulariaceae	Mimulus	Torreyi	Forb	Annual	Native
OSCH	Apiaceae	Osmorhiza	Chilensis	Forb	Perennial	Native
PIPO	Pinaceae	Pinus	ponderosa	Tree	Perennial	Native

Appendix A (cont.): Species list and life history information for all vascular plants occurring within the study site at the Challenge Experimental Forest. Nomenclature follows Hickman (1993) and the species codes were derived from the PLANTS database (USDA-NRCS, 2007b).

Species Code	Family	Genus	Species	Growth form	Lifespan	Origin
POCO4	Polygalaceace	Polygala	Cornuta	Forb	Perennial	Native
POGLR3	Rosaceae	Potentilla	glandulosa ssp. reflexa	Forb	Perennial	Native
PSMEM	Pinaceae	Pseudotsuga	meziesii var. menziesii	Tree	Perennial	Native
PTAQP2	Dennstaedtiaceae	Pteridium	aquilinum var. pubescens	Forb	Perennial	Native
QUCH2	Fagaceae	Quercus	chrysolepis	Tree	Perennial	Native
QUKE	Fagaceae	Quercus	Kelloggii	Tree	Perennial	Native
RHPU	Rhamnaceae	Rhamnus	Purshiana	Shrub	Perennial	Native
RIRO	Grossulariaceae	Ribes	Roezlii	Shrub	Perennial	Native
ROGY	Rosaceae	Rosa	gymnocarpa	Shrub	Perennial	Native
RUDI2	Rosaceae	Rubus	Discolor	Shrub	Perennial	Alien
RULA	Rosaceae	Rubus	Laciniatus	Shrub	Perennial	Alien
RULE	Rosaceae	Rubus	leucodermis	Shrub	Perennial	Native
SCUTE	Lamiaceae	Scuttelaria	sp.	Forb	Perennial	Native
SIMAA	Malvaceae	Sidalcea	malvaeflora ssp asprella	Forb	Perennial	Native
SYMO	Caprifoliaceae	Symphoricarpos	Mollis	Shrub	Perennial	Native
TODI	Anacardiaceae	Toxicodendron	diversilobum	Shrub	Perennial	Native
TRLA6	Primulaceae	Trientalis	Latifolia	Forb	Perennial	Native
UNKF	unk. forb			Forb		
UNKG	unk. graminoid			Graminoid		
VIAM	Fabaceae	Vicia	Americana	Forb	Perennial	Native
VICA5	Vitaceae	Vitis	Californica	Shrub	Perennial	Native
VICIA	Fabaceae	Vicia	sp.	Forb	Perennial	Native
VILOL2	Violaceae	Viola	lobata ssp lobata	Forb	Perennial	Native

Appendix B: Correlations (Spearman's rho) between environmental variables, plant cover estimates and diversity measures for all treatments in a second-growth ponderosa pine forests of northern California.

	n	Herb Cover	Shrub Cover	Richness	Simpson
Midstory Height (cm)	120		–––	–––	–––
Canopy Closure (%)	120	–	––	–––	––
Bare Ground (%)	120		+	+++	+
Woody Debris Cover (%)	120	––			
Litter Cover (%)	120		–	–––	
Forest Floor Depth (cm)	120			––	
Litter Load (Mg ha^{-1})	120			––	
Duff Load (Mg ha^{-1})	120				
Woody Debris Load (Mg ha^{-1})	120				
Min Bole Char Height (cm)*	40	–––		––	
Burn Patchiness Index*	40				
Burn Consumption Index*	40				

* = correlation analyses based only on MAST/RX plot data

+ + + /– – – = $P < 0.001$; + + /– – = $P < 0.01$; and + /– = $P < 0.05$