

Fuels treatment longevity of mechanical mastication and growth response of ponderosa
pine (*Pinus ponderosa*) in northern California

By

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Many fire-prone forests in western North America suffer from hazardous fuel conditions. Mechanical mastication is an increasingly common method of fuels treatment, but little is known regarding long-term effectiveness. A randomized block design at two sites (northern Sierras and southern Cascades) compared ladder fuels and overstory growth among treatments including mastication alone and mastication followed with prescribed fire or herbicide 10 or 11 years post-treatment. Subsequent herbicide application reduced ladder fuels in comparison to mastication alone or with prescribed fire. Prescribed fire further reduced ladder fuels at the southern Cascades site, however, in the northern Sierras post-fire ladder fuels were positively related to overstory absence. Mastication alone effectively released ponderosa pine at the southern Cascades site, whereas neither herbicide nor prescribed fire affected pine radial growth. This study demonstrates the feasibility of prescribed fire and herbicide for increasing treatment longevity of mastication, but also highlights potential limitations and important considerations.

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CHAPTER I

INTRODUCTION

In the western United States widespread low-severity surface fires historically maintained many ponderosa pine (*Pinus ponderosa*) forests and woodlands (Cooper 1960, Agee 1998, Hessburg et al. 2005). A century of timber harvesting, livestock grazing, and an overzealous fire suppression policy has led to increases in tree density, midstory ladder fuels, shade-tolerant species, and the occurrence of large-scale, stand-replacing wildfire (Agee and Skinner 2005, Hessburg et al. 2005, Stephens and Ruth 2005). To combat these changes, various forms and combinations of fuels treatments have been prescribed over unprecedented spatial scales across dry forests of the western United States (Stephens and Ruth 2005).

Fuels treatment effectiveness is largely determined by: 1) reduction of vertical fuel continuity (i.e. ladder fuels) to prevent tree torching; 2) reduction of horizontal fuel continuity and canopy bulk density to prevent crown fire spread; 3) reduction of ground and surface fuels, the latter of which contributes to fireline intensity and rate of spread; and 4) preservation of the largest, most fire-resistant trees (Brown et al. 2004, Agee and Skinner 2005). Furthermore, as the threat of catastrophic fires to human and forest resources has become increasingly recognized, so has the need to incorporate fuels reduction within the management for multiple resource objectives in fire-prone forests (Keyes and O'Hara 2002, Brown et al. 2004, Agee and Skinner 2005).

In forests of northern California, fuels treatment longevity is highly dependent on the regeneration of hardwood shrubs and trees which may respond prolifically via seeding and/or sprouting (Kauffman and Martin 1990, Kane et al. 2010). Given the high cost of initial treatment (Vitorelo et al. 2009), there is a growing need to determine the longevity of these fuels treatments, as well as the influence of subsequent maintenance treatments such as prescribed fire or herbicide. Among fuels treatments, mechanical mastication has become an increasingly common method to reduce standing fuel via mechanical shredding or chipping of standing trees or shrubs. This reduction of ladder fuels to a compact layer of woody debris (Kane et al. 2010) is thought to reduce fireline intensity, rate of spread, and the potential for crown fire ignition (Kreye et al. 2014).

Two important aspects of mechanical mastication are the focus of this study. First, there is a need to determine how mastication alone or in combination with other treatments (i.e. prescribed fire or herbicide) affect live fuels regeneration and potential changes in forest structure and composition. Second, no information is available regarding post-treatment growth and mortality of ponderosa pine across fuels treatments including mastication followed by prescribed fire, mastication followed by herbicide, and mastication alone. Addressing these gaps in our current understanding of mastication will inform land managers on expected outcomes for various approaches to future fuels reduction and restoration in ponderosa pine forests of northern California and potentially elsewhere.

CHAPTER II
WOODY VEGETATION RESPONSE TO MECHANICAL MASTICATION AND
MAINTENANCE TREATMENTS

Introduction

Prolonged fire exclusion and other anthropogenic activities have profoundly altered fire-prone forests of the western United States (Agee and Skinner 2005, Ryan et al. 2013). These activities have increased midstory, overstory, and surface fuels in forests historically maintained by recurring wildfire (Agee and Skinner 2005, Ryan et al. 2013). In northern California, surface fuel accumulation and the increased tree and shrub densities resulting from fire-exclusion currently threaten both ponderosa pine (*Pinus ponderosa*) and mixed-conifer (*Pinus ponderosa*, *Pseudotsuga menziesii*, *Abies concolor*, *Pinus lambertiana*, and *Calocedrus decurrens*) forests (Safford et al. 2012, Stephens et al. 2012). Land managers are also faced with the task of protecting a growing wildland-urban interface (“WUI” hereafter) from the increasing threat of catastrophic wildfire (Agee and Skinner 2005, Reinhardt et al. 2008, Quinn-Davidson and Varner 2012). Due to these factors, fuels reduction and ecological restoration have become increasingly important for forest management and the protection of both human and natural resources from inevitable wildfire events characteristic of the region (Reinhardt et al. 2008).

Mechanical mastication is an increasingly preferred method of fuels treatment since it can address ladder fuels more efficiently than labor-intensive hand-thinning and

can be implemented without the restrictions of prescribed burning, which is fraught with short burn windows, escape risk, and air quality regulations (Busse et al. 2005, Kane et al. 2010, Quinn-Davidson and Varner 2012). Mastication is predominantly used for fuels treatment or fuel break construction, but can also be used to facilitate reintroduction of prescribed fire by reducing ladder fuels that may cause undesirable fire behavior (Kane et al. 2009, Knapp et al. 2012b). Mastication aims to reduce potential fire behavior via decreasing fireline intensity and rate of spread, increasing canopy base height, and decreasing canopy bulk density (Knapp et al. 2012b, Kreye et al. 2014). In addition, masticated residues may buffer mechanical soil compaction, decrease soil runoff, retain nutrients, and potentially inhibit regeneration of shrub and tree seedlings (Hartsough et al. 2008, Reiner et al. 2009, Kane et al. 2010, Knapp et al. 2012b). Unfortunately, benefits gained from mastication may be short-lived if treatments are not maintained, particularly when resprouting shrubs and small trees are prevalent (Keyes and Varner 2006). These shrubs and small trees that establish within open sites can grow rapidly and reduce the longevity of treatments by recovering ladder fuels capable of sustaining high fireline intensity and crown fire ignition (Kane et al. 2010, Syphard et al. 2011).

Objectives for fuels treatment of fire-prone forests include increasing stand resistance to wildfire as well as restoring historic stand structure and species diversity (Agee and Skinner 2005, Hessburg et al. 2005). Prescribed fire can provide a means of reintroducing native disturbance (i.e. low-intensity surface fires) where nutrients are released and woody vegetation reduced (Ryan et al. 2013). Previous studies have demonstrated the added benefits of low-intensity prescribed burning following mechanical treatments since activity fuels, typical of masticated sites (Kane et al. 2009),

are consumed and canopy base heights may be further increased (Allen et al. 2002, Agee and Skinner 2005, Reiner et al. 2009, Fulé et al. 2012, Stephens et al. 2012). Depending on fire intensity, however, initial prescribed fire may contribute fuels via fire-killed trees and branches (Agee and Skinner 2005), and top-killed hardwood species may resprout vigorously (Kauffman and Martin 1990). While many shrub species resprout following topkill, other species, known as obligate seeders, rely entirely on prolific seed production and soil storage until scarification by fire (Keeley and Zedler 1978, Knapp et al. 2012a). Research is needed to determine how prescribed fire following mastication compares to other treatment options with respect to woody fuels regeneration and fuel loading over time.

Our understanding of vegetation response to mastication and mastication with subsequent treatments in ponderosa pine forests is also limited. Studies have found the presence of chipped fuels to reduce abundance (Wolk and Rocca 2009) and diversity (Miller and Seastedt 2009) of native understory vegetation in thinning treatments of ponderosa pine on the Colorado Front Range. Research in northern California has also found changes in plant community composition due to mastication or chipped residues (Potts and Stephens 2009, Kane et al. 2010). In the northern Sierra Nevada, Kane et al. (2010) found prescribed burning and soil incorporation of masticated fuels to significantly increase understory plant diversity compared to control treatments. Conversely, prescribed burning of masticated treatments increased shrub seedling density and non-native species richness compared to mastication alone, likely due to the scarification of stored seedbanks and exposure of mineral soil (Kane et al. 2010). Potts and Stephens (2009) found a higher abundance of non-natives associated with

mastication in comparison to standalone prescribed burning regardless of treatment season in montane chaparral on the Coast Range of northern California. Vegetation response across these studies has been overwhelmingly focused on the short-term, ranging from only 3 to 5 years post-treatment (Miller and Seastedt 2009, Potts and Stephens 2009, Wolk and Rocca 2009, Kane et al. 2010). There is a clear need to reevaluate factors influencing the longevity of mastication over longer time intervals, including the influence of prescribed fire or herbicide on post-treatment vegetation and fuel loading.

Herbicides are an important tool in intensive forest management for chemical site preparation, herbaceous weed control, and early to mid-rotation release treatments (Shepard et al. 2004, Wagner et al. 2006). Herbicide use in northern California has been well studied for its role in site preparation and early release of conifer plantations (Zhang et al. 2013). However, research on the use of herbicides for fuels reduction and the restoration of established, fire-prone forests has been largely focused on pine ecosystems of the southeastern United States (Brose and Wade 2002, Marshall et al. 2008); research on incorporating herbicides as fuels treatments in the western United States has been limited. Studies on herbicide use for fuels reduction highlight effective control of resprouting ladder fuels relative to thinning or prescribed fire, however, as a standalone treatment fire hazard may increase until decomposition of standing dead fuels (Brose and Wade 2002).

The use of herbicides in combination with prescribed fire may address both current and future ladder fuels as both woody fuels and subsequent resprouting are reduced (Brockway and Outcalt 2000, Brose and Wade 2002). Different methods of

herbicide application may differ in their impact on both target and non-target species. For example, Brockway and Outcalt (2000) found spot application of hexazinone followed by prescribed fire to produce the highest herbaceous diversity when compared to broadcasted hexazinone with prescribed fire, or prescribed fire only while trying to reduce turkey oak (*Quercus laevis*) dominance following severe wildfire in a longleaf pine-wiregrass community in central Florida. Freeman and Jose (2009) found similar success with banded applications of various herbicides including imazapyr, sulfometuron methyl, hexazinone, and mixed hexazinone and sulfometuron methyl over planted longleaf pine (*Pinus palustris*) in a Florida flatwoods; however, targeted shrubs had returned to pre-burn levels in just four years following application, suggesting the need for repeated prescribed fire maintenance in this region. These vegetation and fuel dynamics are less understood in western ponderosa pine forests.

Additional research is needed to investigate the potential use of herbicides for fuels management and ecological restoration in fire-prone forests of the western United States. This study addressed several questions related to the longevity of mechanical mastication treatments in the northern Sierra Nevada and southern Cascades: 1) How do mastication alone or mastication followed by prescribed fire or herbicide compare 10 to 11 years post-mastication with respect to basal area, average height, stem density, and species composition of shrub and small trees?; 2) How do canopy openness or residual tree basal area influence shrub and small tree response following mastication and prescribed fire?; and 3) How do treatments compare with respect to forest floor depth and loading 10 to 11 years post-mastication? The answers to these questions have direct implications for the factors controlling fuels treatment longevity of mechanical

mastication in northern California, but they may also provide insight for fuels reduction in other fire-prone ecosystems.

Methods

Site Description

Treatments for this experiment were implemented at two sites in northern California previously described by Knapp et al. (2012b). The Challenge site (39°29'N, 121°13'W; 850 m elevation) was located in the northern Sierra Nevada within the Challenge Experimental Forest of the Plumas National Forest (Fig. 2.1). Challenge was an approximately 50 year old mixed-conifer forest that regenerated naturally following clearcutting and broadcast burning with ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), and incense-cedar (*Calocedrus decurrens*), along with the hardwoods California black oak (*Quercus kelloggii*), tan-oak (*Notholithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*). Dominant shrub species consisted of white-leaf manzanita (*Arctostaphylos viscida*) and deerbrush (*Ceanothus integerrimus*). Soils at Challenge are classified as Sites loams (fine, parasequic, mesic Xeric Haplohumults) derived from metabasic rock (Adams et al. 2010). Site index for ponderosa pine is an estimated 34 m at age 50 (Zhang et al. 2006). Annual precipitation at Challenge averaged 1730 mm with average monthly temperatures ranging from 6 to 21°C.

The Whitmore site (40°37'N, 121°53'W; 760 m elevation) was located in the southern Cascades on private timberland in Shasta County near the town of Whitmore (Fig. 2.1). Whitmore was planted in ponderosa pine approximately 30 years prior to this study following mechanical site preparation and early chemical release from a shrub field

induced by the stand-replacing Morelli Fire in 1968. Whitmore soils are classified as Aiken loams (clayey, oxidic, mesic Xeric Haplohumults) derived from andesitic lahar flows from the eruption of Mt. Lassen (Powers and Reynolds 1999). Average annual precipitation at Whitmore is 1055 mm with average monthly temperatures ranging from 6 to 25°C. Site index of ponderosa pine is an estimated 23 m at age 50 (Powers and Reynolds 1999). Climate at both sites is classified as Mediterranean with characteristic hot, dry summers and cool, wet winters.



Figure 2.1 Map of Challenge and Whitmore sites in northern California.

Experimental Design

Four fuels treatments were applied in a randomized complete block design at Whitmore (sample size=4) and Challenge (sample size=3): mastication only (Mast/Only); mastication followed by herbicide (Mast/Herb); mastication followed by prescribed fire (Mast/Burn); and Control. At each site Control and Mast/Burn treatments were implemented within 0.4 ha units while Mast/Only and Mast/Herb were implemented within smaller 0.2 ha units. Treated units contained five (Mast/Only and Mast/Herb) or ten systematically placed grid points (Control and Mast/Burn) used for sampling.

Mastication was accomplished at both sites with a Rayco horizontal drum masticator with fixed teeth (Rayco Manufacturing Inc., Wooster, OH, US) during winter of 2002 at Challenge and spring of 2002 at Whitmore, with the exception of Mast/Burn units at Whitmore which were masticated in May 2003. Mastication targeted primarily shrubs, but also conifers and hardwood trees less than 15 cm diameter at breast height (1.37 m; hereafter “dbh”). The herbicide treatment was applied at Whitmore and Challenge in March and April of 2004 with a spring application of hexazinone (2.24 kg ai ha⁻¹) and early summer application of tank-mixed glyphosate (4.48 kg ai ha⁻¹) and imazapyr (0.21 kg ai ha⁻¹) applied with a CO₂-pressurized backpack sprayer in 2004. Herbicide was applied at half the target application rate in overlapping, perpendicular directions with 6.1 m swath widths at 20 psi to maximize uniformity of coverage. Prescribed fires were conducted in June 2005 at Challenge and June 2006 at Whitmore. Burns were ignited using strip-head fires spaced 2 to 3 m apart, although some backing fire was used to mitigate unacceptable fireline intensity (Knapp et al. 2012b). Conditions for all burns consisted of low wind speeds (< 5 km h⁻¹) and relative humidity between 32

to 58% (Knapp et al. 2012b). Respective fuel moisture content for 1h, 10h, and 100h woody fuels prior to burns ranged between 5.4 to 14.8%, 8.8 to 17.6%, and 11.3 to 19.8% (Knapp et al. 2012b). Following burning, initial overstory pine mortality (3 years post fire) within treatments ranged between 0 to 10.5% at Whitmore and 8.8 to 91.1% at Challenge (Knapp et al. 2012b). The initial plant community response to Control, Mast/Burn, and Mast/Only treatments at Challenge was analyzed by Kane and others (2010; see details below).

Data Collection

Shrub and Small Tree Abundance

To estimate total shrub and small tree (<10 cm dbh) basal area ($\text{m}^2 \text{ha}^{-1}$) and basal area by species, the number of stems per species and ground line diameters (“GLD” hereafter) were sampled during 2013 (10 or 11 years post-mastication). Sampling was conducted within belt transects centered at each grid point and oriented at a random azimuth (Fig. 2.2). Sampling of larger shrub or small tree species (primarily *Acer macrophyllum*, *Arbutus menziesii*, *Arctostaphylos manzanita*, *Arctostaphylos viscida*, *Ceanothus integerrimus*, *Cornus nuttallii*, *Quercus kelloggii*, and *Notholithocarpus densiflorus*) was stratified by GLD size classes (< 1 cm, 1 to 5 cm, and > 5 cm) to better estimate basal area. Transects contained ten, 1 m \times 1 m quadrats for which up to three measurements of GLD and stem height were recorded for each species or species’ size class. GLD and stem height were measured for each species at the quadrat level by sampling the first three stems encountered in the direction of the transect azimuth. When more than 15 stems were present for a given species, every fifth stem (up to three) was

measured (Fig. 2.2). Stem density was tallied for each species within quadrats and totaled at the transect level (10 m²).

Basal area for each species was calculated by multiplying stem density by the average stem basal area within each transect. When different size classes existed basal area was calculated separately by size class and then combined at the transect level. Transect basal area totals were averaged within each treatment for analysis.

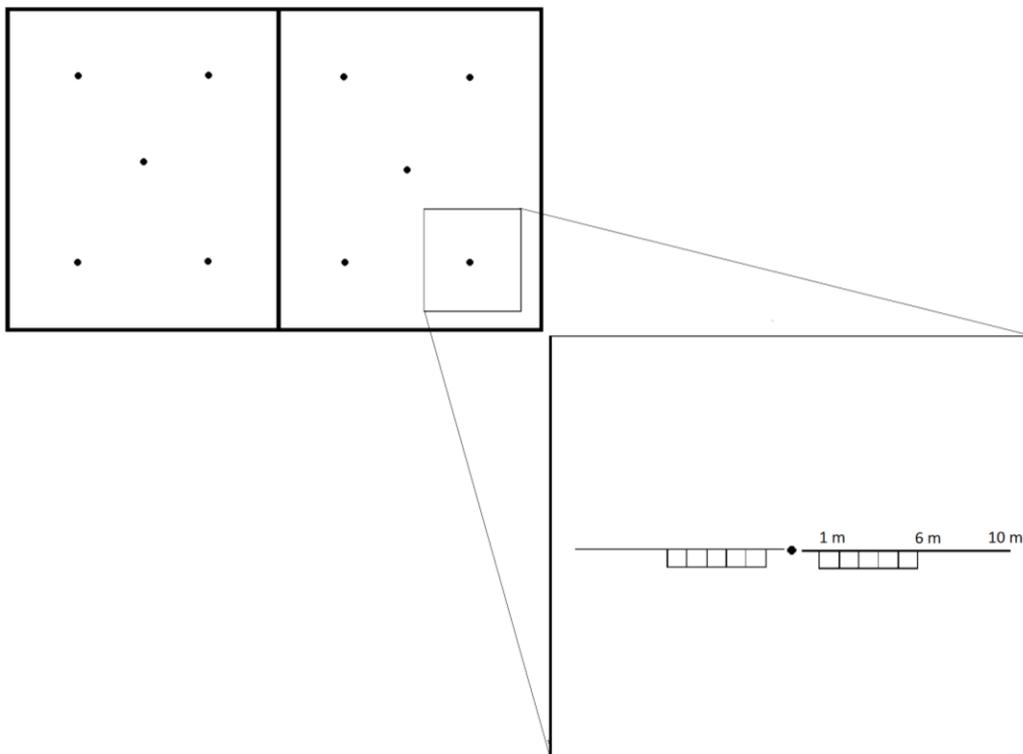


Figure 2.2 Depiction of treatment layout with gridpoints and 10 m² belt transects for vegetation sampling and 20 m planar transect for fuels sampling.

GLD measurements were infeasible for prostrate or mat-forming sub-shrub species, therefore, abundance of these species was measured by percent cover (0-1%, 2-

10%, 11-25, 26-50%, 51-75%, 76-95%, 96-100%; classes) within each of the ten quadrats per transect. Average stem height was calculated by taking the average of all measured stems within transects and transect means were averaged within each treated unit. *Rubus discolor*, *R. leucodermis*, and *R. laciniatus* formed dense thickets and proved difficult for discerning individual stem heights. Therefore, *Rubus spp.* were not included in the analysis of average stem heights along with species of low-growing sub-shrubs (*Ceanothus prostratus*, *Symphoricarpus mollis*, and *Lonicera hispidula*).

Fuel Loading

Surface fuel loading was measured within each treatment unit with a hybrid approach following Kane et al. (2009). In this approach, planar intercept methods (after Brown 1974) were used to estimate loading of 1,000 hour (>7.6 cm diameter) woody fuels along a 20 m transect randomly aligned at each gridpoint as a continuation of the shrub belt transects (Fig. 2.2). Fine woody fuels (1, 10, and 100 hour) and duff and litter were collected within a 0.5 m × 0.5 m frame 4 m from each gridpoint within the randomly oriented belt transect. The collected fine fuels were oven-dried at 85°C for at least 72 hours (until weight reached equilibrium) to obtain dry weights (g) and subsamples were then averaged within each treatment unit to estimate fuel loading (Mg ha⁻¹).

Overstory

To determine potential overstory influence on shrub and small tree growth following prescribed fire, hemispherical canopy photographs were used to estimate canopy closure. Canopy photographs were taken during July of 2013 with a Nikon

D3000 digital camera (Nikon Inc., Melville, NY, USA) and a 4.5 mm Sigma circular fisheye lens (Sigma Corporation of America, Ronkonkoma, NY, USA). Photographs were taken under diffuse light conditions (i.e. prior to sunrise or after sunset) with the camera positioned 1.8 m over each gridpoint in the Mast/Burn treatments at both sites. Foliage and branches occurring within 50 cm of the lens were clipped and removed to allow a more accurate representation of the overstory canopy. Canopy photos obscured by shrub or small tree foliage were removed from analysis (6 of 70). In addition, residual tree basal area was measured with a 2.23 m² ha⁻¹ BAF prism at each gridpoint.

Data Analyses

Treatment differences for shrub and small tree responses (basal area, stem density, average stem height, cover, and species richness) and fuel load were analyzed using a two-way General Linearized (GLM) ANOVA. Response variables not meeting assumptions of equal group variances (Levene's HOV test, $P < 0.10$) were either Log or square root transformed where appropriate (Sokal and Rohlf 1995). Due to small sample size ($n=4$) a more liberal critical value ($\alpha=0.10$) was used for multiple comparison tests to reduce likelihood of Type II error. Multiple comparisons of treatment means were tested using Fisher's Least Significant Difference (LSD) test (Sokal and Rohlf 1995).

To test the null hypothesis of no differences in woody species composition among fuels treatments at each site, blocked multiple response permutation procedures (MRPPs) were conducted in PC-ORD 6.08 (McCune and Mefford 2011). For MRPPs, treatments were defined as groups and Euclidean distance measures were median aligned by block. To reduce noise in the data set, rare species occurring in less than 5% of transects were removed from analysis at each site. Since species abundance was measured using both

basal area and cover, data were relativized by the maximum values within treatment groups for analysis. Effect size for MRPPs, indicated by the chance-corrected within-group agreement A , describes the within-treatment homogeneity compared to random expectation (McCune et al. 2002). If blocked MRPP results confirmed significant treatment differences in species composition, a blocked indicator species analysis (ISA) was used to determine species-treatment relationships. ISA calculates an indicator value (IV) for each species per treatment based on combined calculations of relative abundance (i.e. basal area or cover) and relative frequency within each group (McCune et al. 2002). The IVs range from 0 to 100 with 100 indicating a species found consistently within only one given treatment (McCune et al. 2002). Statistical significance of IVs was determined using Monte Carlo tests with 5000 randomizations.

Gap Light Analyzer Version 2.0 was used to compute canopy openness (percentage of open sky seen 180° from 1.8 m above the forest floor) for each gridpoint (Frazer et al. 1999). Linear regression was used to explore potential relationships between canopy openness (%) or overstory basal area ($\text{m}^2 \text{ha}^{-1}$) and total shrub and small tree basal area ($\text{m}^2 \text{ha}^{-1}$) (constrained to the proximal 6 m² instead of the full 10 m² belt transect) within the Mast/Burn treatments at both Challenge and Whitmore.

Results

Live Woody Fuels

Fuels treatments showed marked differences between the two sites with respect to shrub and small tree regeneration 10 to 11 years following mastication. Total shrub and small tree basal area did not differ among treatments at Challenge ($F=3.04$, d.f.=2, $P=0.11$). At Whitmore, Mast/Only and Mast/Burn treatments resulted in significantly

lower shrub and small tree basal area than Control; Mast/Herb was lower than all other treatments ($F=16.48$, d.f.=3, $P=0.0005$) (Table 2.1).

Treatments at Challenge did not differ with respect to average stem height ($F=0.90$, d.f.=2, $P=0.49$). Average stem heights at Whitmore were significantly different among all treatments ($F=26.08$, d.f.=3, $P<0.0001$), with the tallest stems in Control followed by Mast/Only, Mast/Burn, and Mast/Herb (Table 2.1).

Stem density of shrub and small trees at Challenge was significantly lower for Mast/Herb than in either Mast/Burn or Mast/Only ($F=4.50$, d.f.=2, $P=0.056$). At Whitmore, stem density for Mast/Only was significantly greater than Control; Mast/Herb was significantly lower than other treatments ($F=12.09$, d.f.=3, $P=0.0016$) (Table 2.1).

Woody Species Composition

Species richness of native shrub and small trees differed among treatments at both Challenge ($F=3.48$, d.f.=2, $P=0.09$) and Whitmore ($F=29.43$, d.f.=3, $p < 0.0001$) (Table 2.1). At Challenge, native woody species richness was highest in Mast/Burn, whereas, at Whitmore richness was greatest with Mast/Only, intermediate with Control and Mast/Burn, and lowest with Mast/Herb (Table 2.1). Basal area of the non-natives *Rubus discolor* and *Rubus laciniatus* did not differ significantly by treatment at either Challenge ($F=2.40$, d.f.=2, $P=0.17$) or Whitmore ($F=1.00$, d.f.=3, $P=0.44$) (Table 2.1). Results of MRPPs also revealed significant differences in community composition of woody species among treatments at both Challenge ($A=0.09$, $P=0.01$) and Whitmore ($A=0.19$, $P=0.002$). Blocked indicator species analyses revealed significant species-treatment relationships with *Ceanothus integerrimus* highly associated with Mast/Burn at Challenge and *Arctostaphylos viscida* associated with the Control at Whitmore (Table 2.2).

Overstory and Woody Species Response

Total shrub and small tree basal area was positively related to canopy openness in the Mast/Burn treatments at Challenge ($F=45.84$, d.f.=21, $P<0.0001$; $R^2=0.69$) (Fig. 2.3), but not at Whitmore ($F=1.58$, d.f.=38, $P=0.22$; $R^2=0.04$) (Fig. 2.4). Total shrub and small tree basal area was negatively related to overstory basal area at Challenge ($F=49.82$, d.f.=28, $P<0.0001$; $R^2=0.64$) (Fig. 2.5). At Whitmore, a positive relationship between total shrub and small tree basal area and overstory basal area was significant, however the variance explained was low ($F=3.56$, d.f.=38, $P=0.067$; $R^2=0.09$) (Fig. 2.6).

Surface Fuels

Total forest floor fuel loading (duff, litter, and 1-100 hour woody fuels) did not differ significantly by treatment at Challenge ($F=2.50$, d.f.=2, $P=0.16$) or Whitmore ($F=1.91$, d.f.=3, $P=0.20$) (Fig. 2.7). Loading of 1,000 hour fuels did not differ significantly by treatment at Challenge ($F=2.63$, d.f.=2, $P=0.14$) or Whitmore ($F=0.06$, d.f.=3, $P=0.98$). However, Mast/Burn clearly resulted in higher levels of 1,000 hour fuels for some units at Challenge due to fire-induced mortality and subsequent recruitment of downed boles from dead overstory trees (Fig. 2.8).

Table 2.1 Small tree and shrub response to fuels treatments at Challenge and Whitmore.

Response Variable	Challenge (n=3)					Whitmore (n=4)				
	Control	Mast/ Only	Mast/ Burn	Mast/ Herb	P-Value	Control	Mast/ Only	Mast/ Burn	Mast/ Herb	P-Value
Total Basal Area (m ² ha ⁻¹) *	9.6 (3.05)	5.0 (1.60)	12.7 (6.15)	2.4 (1.14)	0.11	21.5 ^a (7.48)	3.8 ^b (0.65)	1.3 ^b (0.35)	0.3 ^c (0.15)	0.0005
Stem Height (m) *	0.79 (0.29)	0.54 (0.17)	0.66 (0.10)	0.40 (0.06)	0.49	1.31 ^a (0.20)	0.57 ^b (0.09)	0.35 ^c (0.06)	0.20 ^d (0.04)	< 0.0001
Stem Density m ⁻² **	4.9 ^{bc} (1.02)	10.0 ^{ab} (3.15)	12.2 ^a (2.59)	4.1 ^c (0.91)	0.056	4.1 ^b (0.82)	7.6 ^a (0.63)	6.5 ^{ab} (1.30)	1.6 ^c (0.73)	0.0016
Native Spp. Richness	4.1 ^b (1.32)	5.2 ^b (0.53)	7.2 ^a (0.55)	4.9 ^b (0.88)	0.09	3.7 ^b (0.30)	4.6 ^a (0.42)	3.85 ^b (0.18)	2.4 ^c (0.16)	< 0.0001
Non-native Basal Area (m ² ha ⁻¹)	0.58 (0.48)	1.46 (0.77)	0.19 (0.10)	0.65 (0.55)	0.17	0.16 (0.16)	0.09 (0.09)	0.0007 (0.0007)	0.17 (0.17)	0.44

Note: Bars represent standard error. Unique superscript letters represent significant differences determined by Fisher's LSD multiple comparison tests ($\alpha=0.10$) (* denotes Log transformation; ** denotes square root transformation).

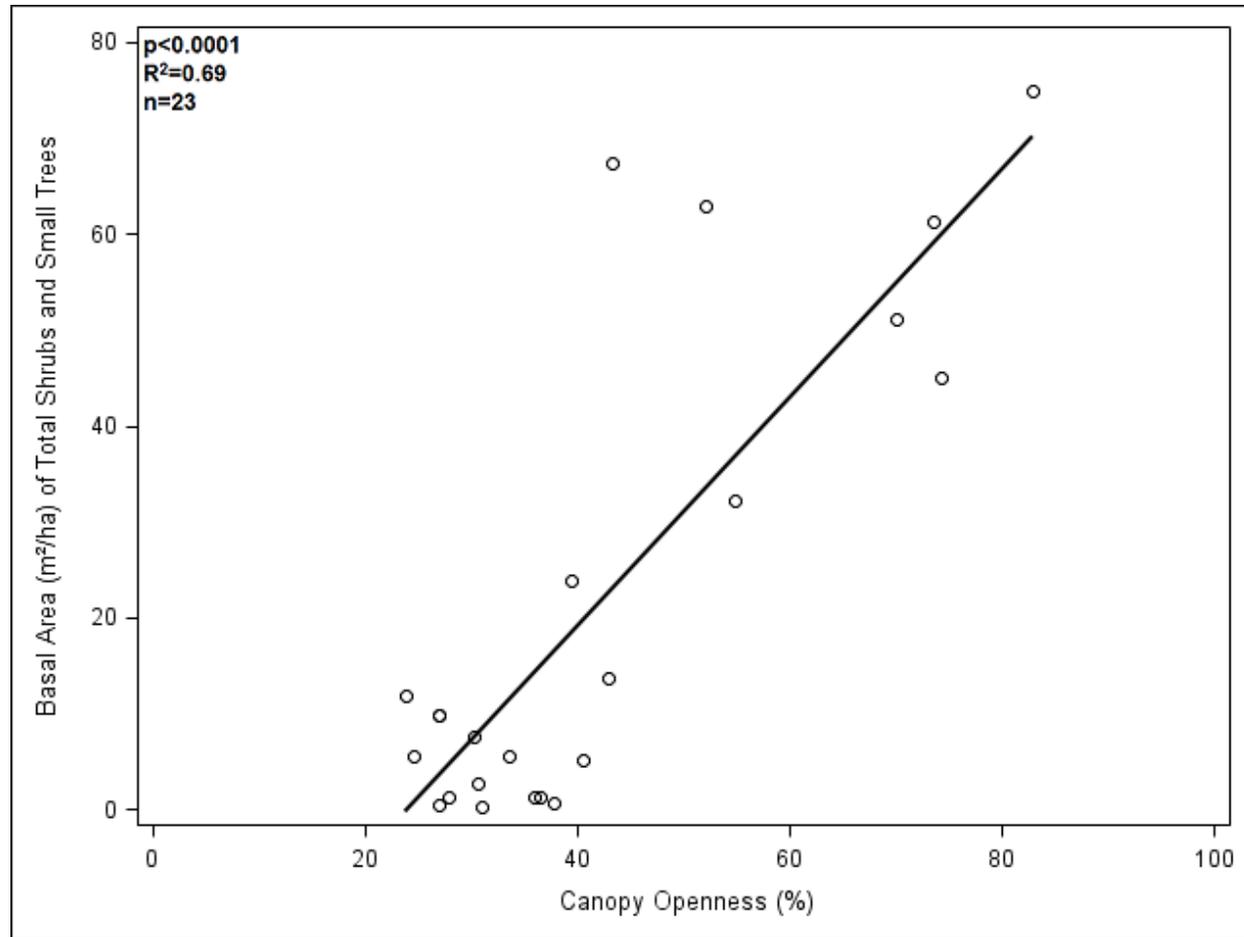


Figure 2.3 Relationship between percent canopy openness and total shrub and small tree basal area at the transect level for mastication and prescribed fire treatments at Challenge.

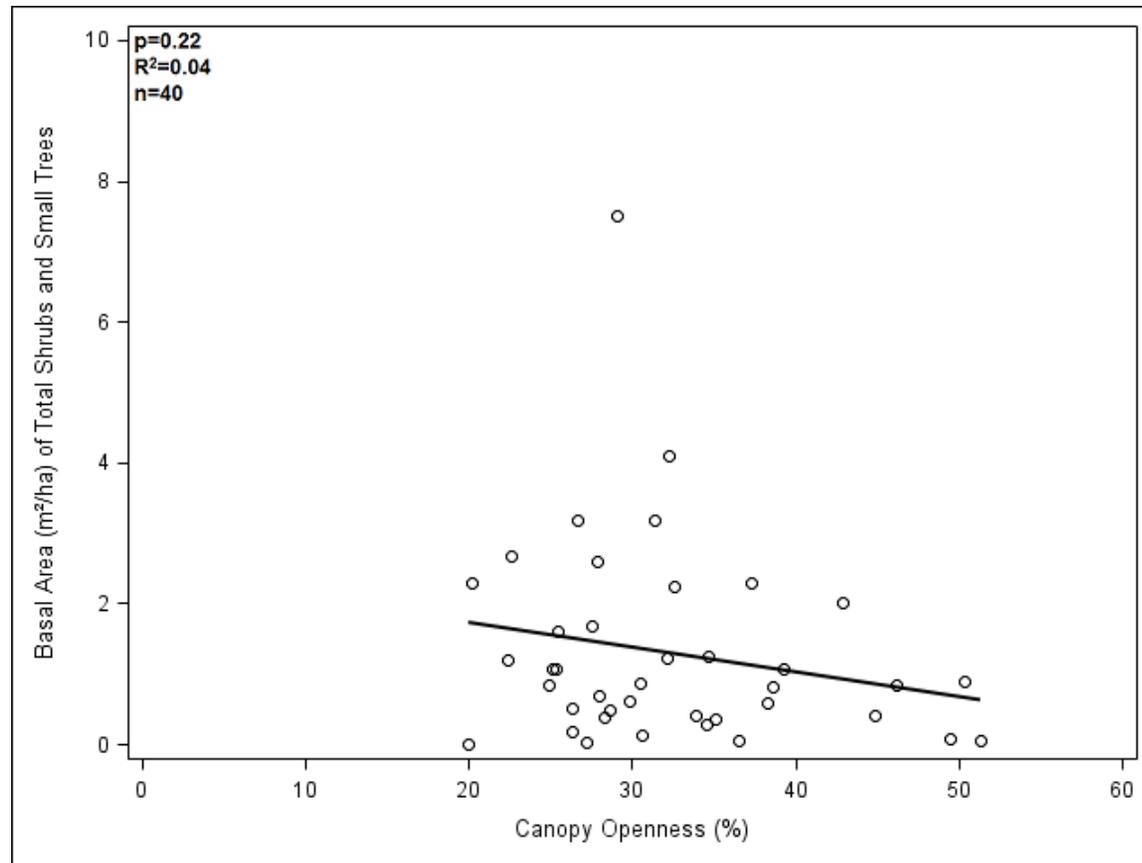


Figure 2.4 Relationship between percent canopy openness and total shrub and small tree basal area at the transect level for mastication and prescribed fire treatments at Whitmore.

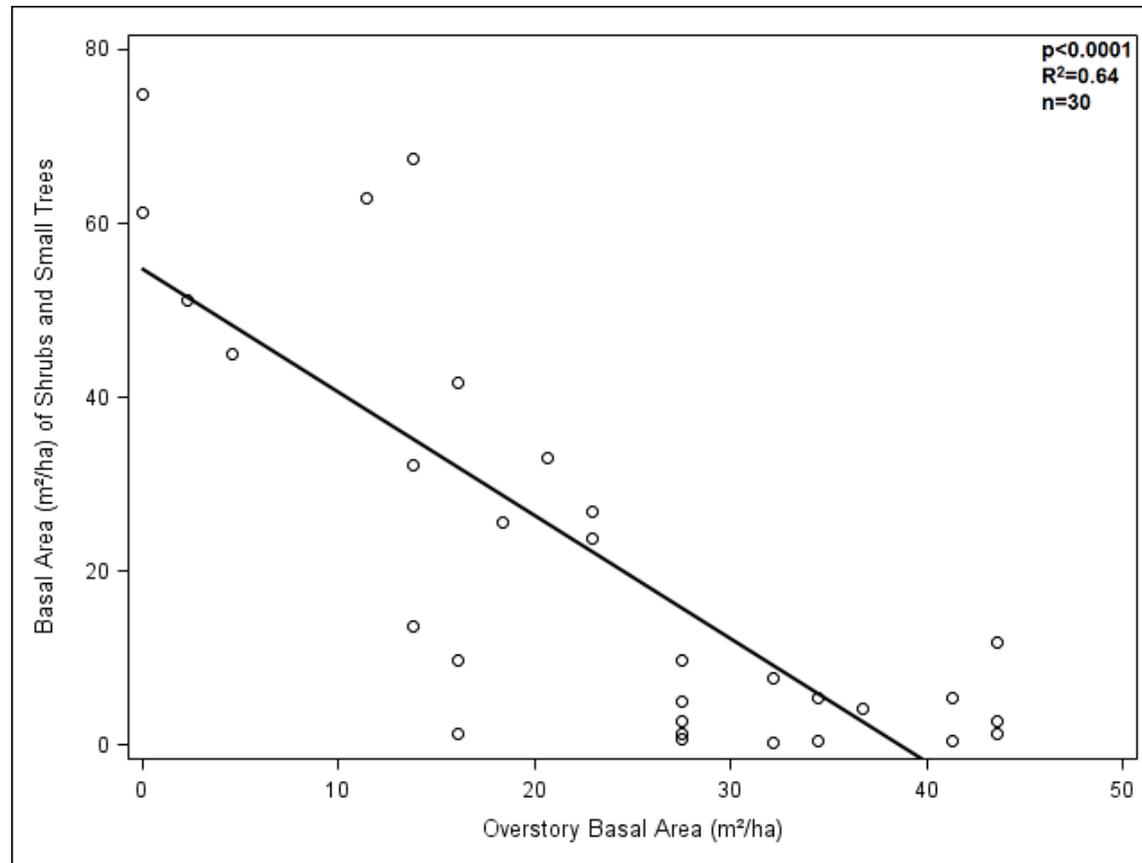


Figure 2.5 Relationship between overstory basal area and total shrub and small tree basal area at the transect level for mastication and prescribed fire treatments at Challenge.

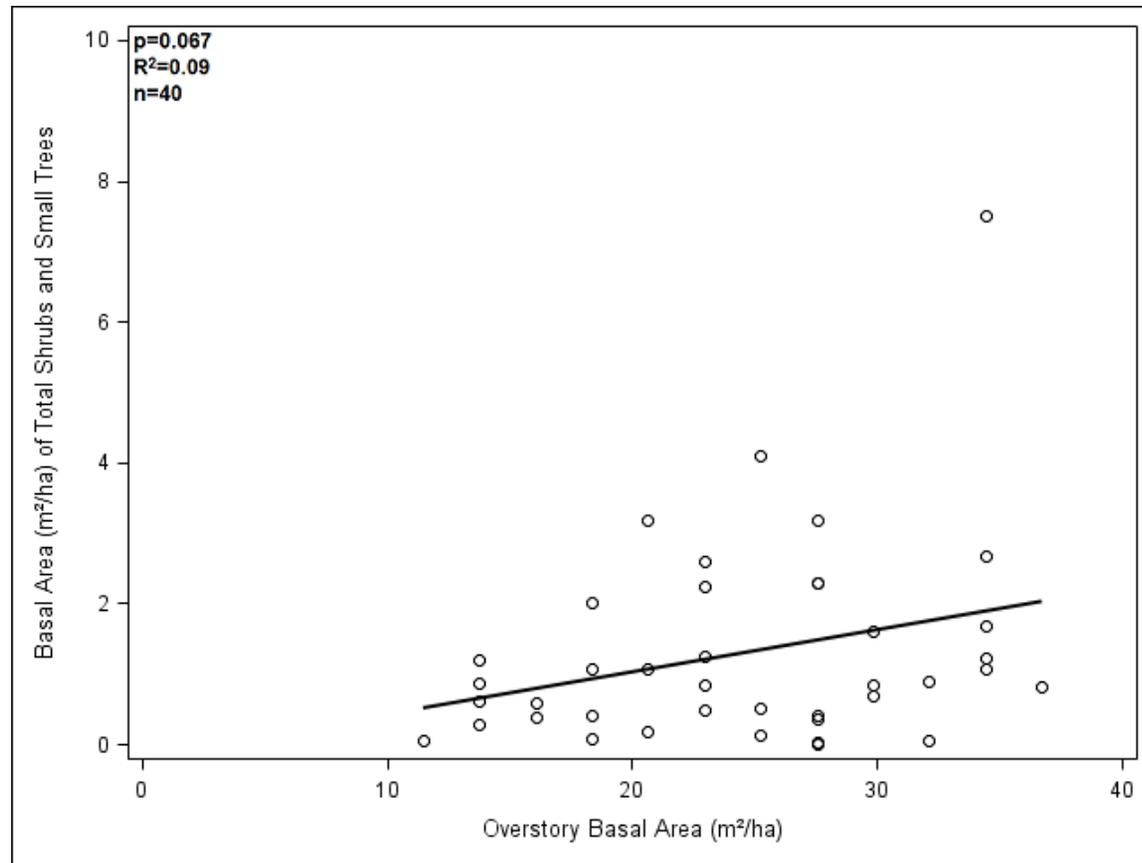


Figure 2.6 Relationship between overstory basal area and total shrub and small tree basal area at the transect level for mastication and prescribed fire treatments at Whitmore.

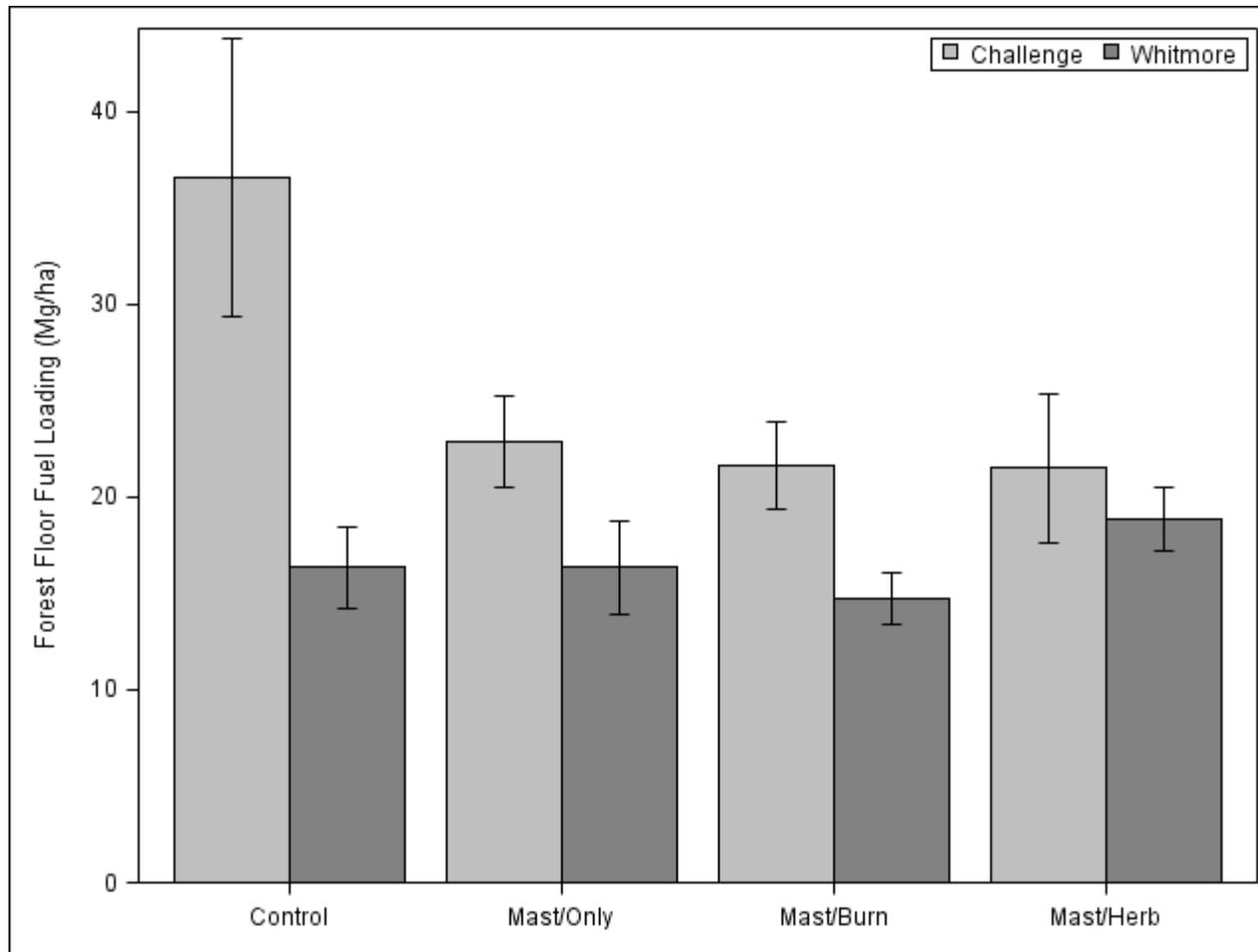


Figure 2.7 Average forest floor fuel loading (litter, duff, and fine woody fuels) by treatment at Challenge and Whitmore.

Note: Bars represent standard error. No significant differences were detected among treatments at either site.

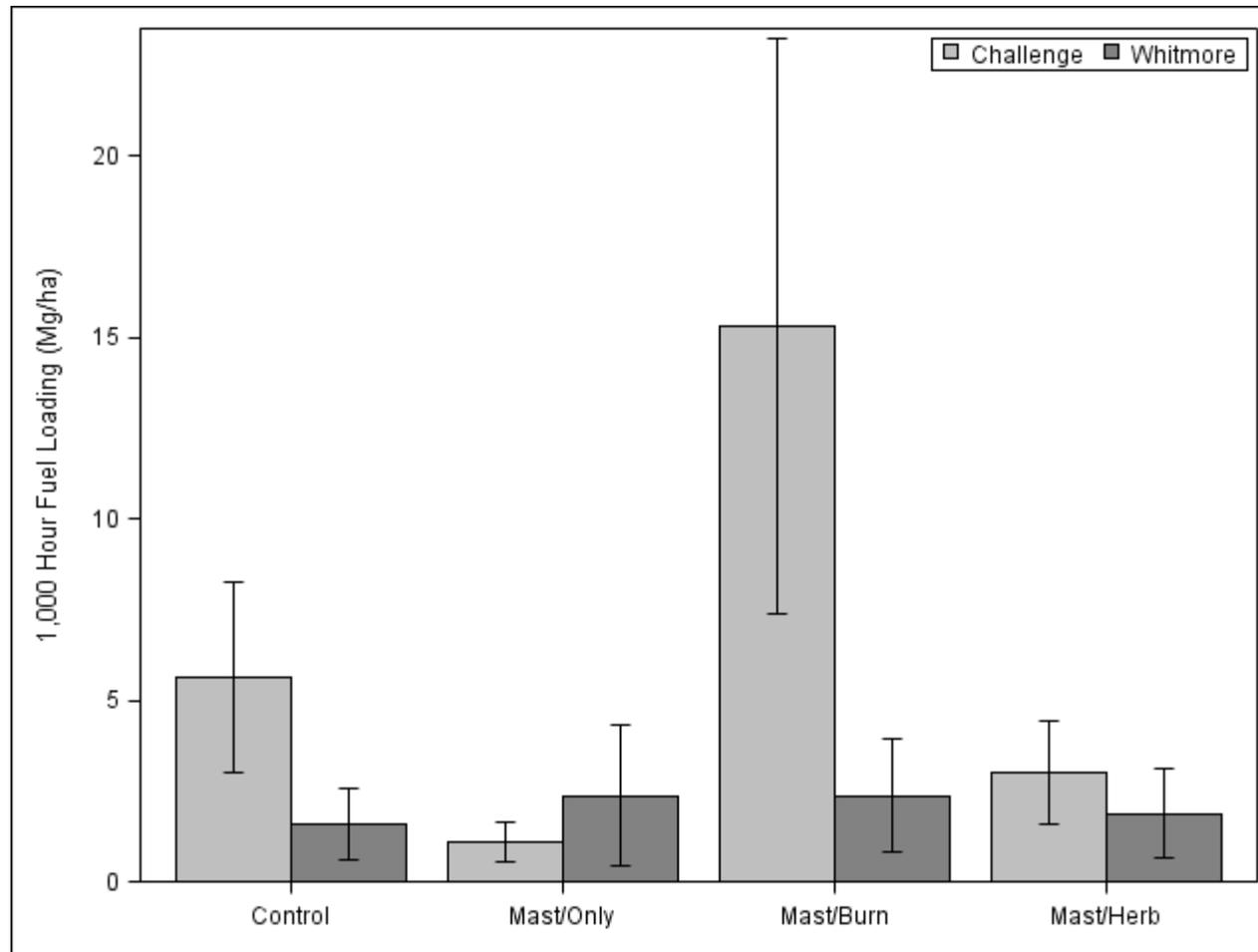


Figure 2.8 Average loading of 1,000 hour fuels by treatment at Challenge and Whitmore.

Note: Bars represent standard error. No significant differences were detected among treatments at either site.

Table 2.2 Results of blocked indicator species analysis (ISA) by site.

Species	Whitmore			Species	Challenge		
	I.V.	Treatment	P-Value		I.V.	Treatment	P-Value
<i>Arctostaphylos viscida</i>	90.1	Control	0.018	<i>Ceanothus integerrimus</i>	95.7	Mast/Burn	0.065
<i>Ceanothus cordulatus</i>	61.2	Mast/Only	0.065	<i>Ribes roezlii</i>	50.4	Mast/Only	0.064
<i>Ceanothus prostratus</i>	48.1	Mast/Only	0.015				
<i>Toxicodendron diversilobum</i>	51.1	Mast/Only	0.096				

∞ Note: P-values represent the probability of finding an indicator value equal to or greater than that observed based on a Monte Carlo test of 5000 randomizations ($\alpha=0.10$). Indicator values range from 0 to 100 with 100 meaning complete fidelity to one treatment.

Discussion

Results of this study suggest the treatment longevity of mechanical mastication was affected not only by the method of maintenance, but was highly dependent on site-specific factors, namely the productivity and species assemblage characterizing each site. Challenge, a mixed-conifer forest in the northern Sierras, had higher site productivity and woody species diversity than Whitmore, a lower elevation ponderosa pine plantation in the southern Cascades. Basal area of shrub and small trees was consistently higher across treatments at Challenge, with the exception of the control units.

Control units at Challenge contained many hardwood trees beyond the diameter limit (10 cm dbh) imposed by shrub and small tree sampling methods. These larger ladder fuels would undoubtedly facilitate torching, thereby increasing the likelihood of active crown fire (Brose and Wade 2002, Agee and Skinner 2005). Unfortunately, the sampling limitations at Challenge likely affected comparisons among Control and fuels treatments for shrub and small tree response variables. Results from treatment comparisons at Challenge should therefore be interpreted with caution.

One factor largely dictating the differences in site-specific response of woody vegetation was the abundance or absence of problematic resprouting hardwoods. Challenge supported a large number of sprouting species (i.e. *Acer macrophyllum*, *Arbutus menziesii*, *Cornus nuttallii*, *Quercus kelloggii*, and *Notholithocarpus densiflorus*), whereas resprouting species at Whitmore were fairly limited (*Toxicodendron diversilobum* and *Quercus kelloggii*).

At Challenge treatment differences with respect to shrub and small tree basal area only approached significance ($P=0.11$), likely due in part to small sample size, even

though basal area was 530% higher on average following Mast/Burn than Mast/Herb (Table 2.1). Differences found with respect to stem density suggest herbicide application following mastication had lasting control over woody vegetation response even though reductions in basal area were not significant. Results from Kane et al. (2010) found a significant increase in stem density one year following prescribed burning in comparison to mastication only at Challenge, however, these differences were confounded by differences in time since treatment. With increased time since treatments our results suggest substantial mortality in shrub stems from one year post-fire (30.7 stems m⁻²) to eight years post-fire (4.1 stems m⁻²), but only a minimal change in stem density following mastication only (11.7 stems m⁻² to 10.0 stems m⁻²) (Kane et al. 2010) (Table 2.1). These high mortality rates following an initial pulse of shrub germination is consistent with research by Potts et al. (2010) who found a disproportionate amount of shrub seedling mortality two to three years following mastication and spring prescribed fire in comparison to mastication only in *Adenostoma* dominated chaparral in the northern California Coast Range.

Mastication at Whitmore resulted in substantial reduction of shrub and small tree basal area and height in comparison to Control. Shrub and small tree response to mastication was dominated by shade-tolerant poison-oak (*Toxicodendron diversilobum*) (Table 2.2), but basal sprouts were likely reduced by lethal heating during prescribed burning (Kauffman and Martin 1990) and were nearly eliminated when mastication was followed by herbicide. Mastication alone effectively released planted overstory pines at Whitmore from competition with large, sclerophyllous *A. manzanita* and *A. viscida* shrubs (Chapter III). These problematic shrubs attained maximum height in the Control

treatments, but as shade-intolerant obligate seeders, these species were sufficiently controlled by mastication alone and subsequent canopy development at Whitmore.

In contrast to responses at Whitmore, Mast/Herb was less effective at Challenge for reducing the basal area of resprouting species. Application rates of imazapyr at both sites were less than those typically used for controlling hardwood competition in this region (DiTomaso et al. 2004), however, the lower rates used in this study were necessary to prevent injury to desirable overstory hardwoods (e.g. *Quercus kelloggii*) and ponderosa pine. Damage to non-target species is a major concern for herbicide use in forestry (Shepard et al. 2004) and improper application may have negative consequences for fuels treatments seeking to restore native plant biodiversity.

Evaluation of mastication and subsequent fuels treatments is highly dependent on management objectives, and therefore, treatment longevity may be based not only on fuels reduction, but also impacts on ecosystem processes, native species diversity, and the long-term resilience of fire-prone forests (Brown et al. 2004, Agee and Skinner 2005, Kane et al. 2010). Fuels treatments not only influenced the structure of live fuels but also the composition of woody species. In this region many obligate seeding species rely on long-term seed banking with germination triggered by disturbance-mediated environmental factors such as light or heat (Keeley and Zedler 1978, Kauffman and Martin 1990, Knapp et al. 2012a), while other species rely heavily on the ability to resprout vigorously in response to topkill (Kauffman and Martin 1990).

Prescribed fire following mastication at Challenge increased the richness of shrub and small tree regeneration over the 10 to 11 year period. It is likely that both the heterogeneity in fuel consumption (Thaxton and Platt 2006), and increased light (Abella

and Springer 2015) due to overstory mortality affected species response at Challenge. For instance, *A. viscida* and *C. integerrimus* at Challenge were most prevalent in the Mast/Burn treatments which experienced substantial fire-induced overstory mortality (Chapter 3) and their abundance likely resulted in part due to heat-triggered germination (Keeley 1987, Kauffman and Martin 1990, Moreno and Oechel 1991).

This study also demonstrates the importance of residual overstory when considering fuels treatment longevity of prescribed fire treatments. Not surprisingly, decreased overstory basal area and increased canopy openness led to a more vigorous response from shrubs and small trees in the Mast/Burn units at Challenge. Minimal levels of overstory mortality from prescribed fire may be desired in order to reduce canopy bulk density and the likelihood of active crown fire, particularly if overstory thinning is not feasible (Allen et al. 2002, Reinhardt et al. 2008). In addition, fire-killed snags and downed woody debris provide valuable habitat which may be desired depending on management objectives (Raphael and White 1984, Lewis 1998). It is not certain why shrub and small trees at Whitmore did not respond similarly to overstory basal area or canopy openness. Limitations of site productivity and previous vegetation control may have influenced woody species response at Whitmore.

Kane et al. (2010) found a significant reduction in litter depth in the Mast/Burn treatment relative to Mast/Only or Control one year following prescribed burning at Challenge. However, total loading of surface and ground fuels (<1,000 hour) 10 to 11 years post-mastication did not differ among treatments at either Challenge or Whitmore, suggesting that initial surface fuel reductions from prescribed fire were short-lived. Conversely, high rates of overstory mortality at Challenge (34.7%; Chapter III)

corresponded with high levels of 1,000 hour fuel loading for some Mast/Burn units at Challenge. While 1,000 hour fuels do not typically contribute to fireline intensity, smoldering combustion of large diameter woody debris may negatively impact both soil and overstory trees (Monsanto and Agee 2008). Benefits from prescribed fire should therefore, be considered in light of the resources necessary for repeated entries in order maintain reduced levels of surface fuels (Brose and Wade 2002).

Management Implications

Fuels treatments such as mastication are being implemented over unprecedented scales in order to protect communities and restore ecosystem function within fire-prone forests. Objectives for fuels reduction at the WUI may have more emphasis on creating fire-safe communities than ecological restoration, particularly since opportunities for prescribed fire may be limited due to liability concerns over smoke and escape risks (Reinhardt et al. 2008, Quinn-Davidson and Varner 2012). In areas such as northern California, mechanical fuels reduction within the increasing WUI are costly to implement (Vitorelo et al. 2009) and maintenance of these treatments is often neglected.

Resprouting species are particularly problematic within masticated treatments, since, unlike obligate-seeding species, they are less likely to be inhibited by mulched residues (Kane et al. 2010) and periodic topkill may increase the lifespan of certain species adapted to recurring wildfire (Kauffman and Martin 1990).

Results of this study demonstrate the utility of herbicide treatment for increasing fuels treatment longevity by reducing the abundance of woody species following mastication. Herbicides use for fuels treatment maintenance will be most appropriate for the protection of infrastructure at the WUI since live standing fuels decrease

opportunities for successful suppression (Brose and Wade 2002, Reinhardt et al. 2008). Herbicide formulations and methods of application other than those used in this study might have provided greater control of resprouting shrubs and small trees while mitigating impacts on woody species diversity. For example, DiTomaso et al. (2004) tested different rates and application methods of imazapyr for controlling tanoak and California black oak in the Sierra and Cascade ranges. They found control was significantly improved with the use of an adjuvant in direct spraying, stem injection was the most effective application method, and late season stem injections were most successful at controlling basal resprouting (DiTomaso et al. 2004). Further research is needed to determine herbicide effects on live woody fuels and species diversity in sensitive areas that prohibit prescribed fire use.

Mastication may be an effective means to restore forest structure, particularly if used to facilitate prescribed fire by reducing fireline intensity and increasing burn windows (Knapp et al. 2012b). Mechanical treatments like mastication without prescribed fire maintenance may be less appropriate for management objectives of wildland fuels since mastication primarily serves the purpose of suppression and does not provide the numerous ecological benefits derived from prescribed fire (Brose and Wade 2002, Reinhardt et al. 2008). Since surface fuels are increased by mastication, the implementation of this treatment without subsequent prescribed fire may pose serious issues for overstory resilience to wildfire since increased surface fuels may lead to lethal soil heating and excessive mortality (Brose and Wade 2002, Agee and Skinner 2005, Busse et al. 2005, Reiner et al. 2012). Mastication has been shown to have either neutral or negative impacts on the abundance and diversity of native herbaceous understory due

to the presence of mulched residues (Miller and Seastedt 2009, Potts and Stephens 2009, Wolk and Rocca 2009, Kane et al. 2010). To mitigate negative impacts on native herbaceous species prescribed fire following mastication should be used to increase species richness and abundance (Kane et al. 2010). Lastly, preservation of overstory basal area in order to exclude the regeneration of ladder fuels should also be weighed against the benefits of light availability on understory diversity (Kane et al. 2010, Abella and Springer 2015) in addition to the risk of active crown fire in a horizontally continuous canopy (Agee and Skinner 2005).

Conclusions

Mastication as a stand-alone fuels treatment may be beneficial for moderating fire behavior and aiding fire suppression; however, the lifespan of masticated fuels treatments may be increased with herbicide or prescribed fire depending on site specific factors such as site productivity, reproductive strategies of dominant shrubs, and the presence of residual overstory. More research is needed to determine how different herbicides and application methods may be used to effectively reduce live woody fuels in fire-prone ecosystems threatened by excessive fuel loading without harming native biodiversity. Reintroduction of prescribed fire following mastication is an ideal follow-up treatment since excessive activity fuels threaten overstory resilience to wildfire (Agee and Skinner 2005, Reiner et al. 2012). Promoting native disturbance regimes via prescribed fire may positively impact native biodiversity. However, conservative burning practices should be used to avoid excessive overstory mortality in masticated stands since live woody fuels may respond vigorously to seed scarification and newly available light and soil moisture. Prescribed fire must also be periodic in order to maintain fuel loads at acceptable levels.

Future research should assess the value of mastication for fire suppression as well as the potential combinations of prescribed fire and herbicide for fuels reduction at the WUI.

CHAPTER III
PONDEROSA PINE GROWTH AND MORTALITY IN RESPONSE TO
MECHANICAL MASTICATION AND MAINTENANCE
TREATMENTS

Introduction

Large-scale increases in tree density, shade tolerant species, and stand-replacing crown fires have become increasingly common in fire-prone forests of the western United States (Agee and Skinner 2005, Hessburg et al. 2005, Stephens and Ruth 2005). To combat these changes and restore natural processes, various forms and combinations of fuels treatments have been prescribed over unprecedented spatial scales across dry forests of the western United States (Stephens and Ruth 2005). One objective of fuels treatments is to increase post-wildfire survival of fire-resistant conifers via thinning and/or prescribed fire (Agee and Skinner 2005, Strom and Fulé 2007, Safford et al. 2012, Stevens et al. 2014). Mechanical mastication has become an increasingly popular approach to reduce fuel continuity via shredding or chipping ladder fuels (Kane et al. 2009). In spite of its increased use, little is known about the effects of mastication or mastication with subsequent treatments on growth and survival of residual ponderosa pine, which are among the most fire-resistant of conifer species in North America (Schwilk and Ackerly 2001, Brown et al. 2004).

Retention of large residual trees is a critical component of fuels treatment longevity (Agee and Skinner 2005). Large trees within treatments cast shade, deterring potential shrub and tree regeneration that reduce treatment longevity (Agee et al. 2000, Allen et al. 2002, Agee and Skinner 2005, Hessburg et al. 2005). Retained canopy cover also moderates potential wildfire behavior by reducing wind speeds and solar heating of the forest floor (Agee and Skinner 2005). Retained trees provide structural heterogeneity resulting in decreased canopy bulk density and wildlife habitat. Lastly, the long-term persistence of fuels treatments is dependent on the resistance of retained trees to future disturbance such as pest outbreaks or wildfire (Brown et al. 2004).

Different methods of fuels reduction may have distinct impacts on residual tree growth by serving the secondary purpose of releasing overstory trees from competition. Given that post-fire survival is known to be positively correlated with tree size and bark thickness (Peterson and Ryan 1986, Ryan and Reinhardt 1988, Jackson et al. 1999), fuels treatments may increase forest resilience over the long-term by promoting larger, more fire-resistant trees (Agee and Skinner 2005). Investigating the overstory dynamics of fire-resistant species such as ponderosa pine in masticated fuels treatments is critical both in terms of restoring historic conditions and increasing fuels treatment longevity.

Herbicides have become an important tool for forest management in both site preparation and competing vegetation control (McDonald and Fiddler 1993, Wagner et al. 2006). Both private and public forests in northern California have relied on herbicides to artificially regenerate forests following wildfire and clearcutting. A central justification for herbicide use in this region is the abundance of pioneer hardwood shrub and tree species which compete aggressively with conifers for limited soil moisture

following disturbance events (McDonald and Fiddler 1993, Powers and Reynolds 1999, Zhang et al. 2013). The use of herbicides following mastication may increase treatment longevity by stalling ladder fuel establishment and growth and may provide the added benefit of increasing average tree size and, consequently, future stand resistance to wildfire.

Limited research has focused on the response of residual trees to prescribed fire in masticated fuel beds. In northern California, Busse et al. (2005) found duration and penetration of lethal heating ($>60^{\circ}\text{C}$) during prescribed burning of masticated shrubs was positively related to fuel depth and negatively related to soil moisture. In this same region, Knapp et al. (2012) found degree of crown scorch and tree size as the strongest predictors of residual tree mortality three years after late spring prescribed burning in masticated stands of ponderosa pine. Reiner et al. (2012b) investigated mortality of planted ponderosa pine in the southern Sierra Nevada two years following mastication and prescribed fire with and without a raking treatment. Pine mortality rates two years following treatments were 48.6, 26.5, and 0.7 percent for mastication with prescribed burning, mastication with raking and prescribed burning, and control, respectively, although differences between raked and unraked treatments were not significant (Reiner et al. 2012). Kobziar et al. (2009) modelled predicted fire behavior under 90th and 97.5th percentile weather conditions following fuels treatments including mastication only, mastication with prescribed fire, prescribed fire only, and control in planted ponderosa and Jeffrey pine (*Pinus jeffreyi*) in the central Sierras. Predicted rates of mortality were highest in mastication only, lower in the control, and lowest in the prescribed fire treatments across size classes of residual trees, demonstrating the importance of

prescribed fire for increasing overstory resilience. These limited studies offer a glimpse of potential post-treatment mortality, but are limited to short time spans (i.e. all \leq three years post-treatment).

While there is a dearth of information on post-treatment mortality, there is even less information on how individual trees grow following treatments. In spite of the wealth of information on tree responses to fuels treatments (Swezy and Agee 1991, Busse et al. 2000, Sala et al. 2005, Schwilk et al. 2009b), I am unaware of any research on post-treatment growth of ponderosa pine following mastication or mastication followed by herbicide or prescribed fire.

This study addresses the following questions and their implications for ponderosa pine fuels management in the northern Sierra Nevada and southern Cascades: 1) How is subsequent stem growth and crown form of ponderosa pine influenced by fuels treatments including mastication and mastication followed by herbicide or prescribed fire?; 2) What is the influence of fire damage in the form of crown scorch on subsequent growth of residual ponderosa pine subject to mastication and prescribed fire?; 3) What are long-term (seven to eight years post-fire) mortality rates of residual ponderosa pine subject to mastication and prescribed fire ?

Methods

Site Description

Treatments were implemented at two study sites in northern California previously described by Knapp et al. (2012b). The Challenge site (39°29'N, 121°13'W; 850 m elevation) is located in the northern Sierra Nevada within the Challenge Experimental Forest of the Plumas National Forest. Challenge was an approximately 50 year old

mixed-conifer forest regenerated naturally following clearcut and broadcast burning with ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), and incense-cedar (*Calocedrus decurrens*). Common hardwoods include California black oak (*Quercus kelloggii*), tan oak (*Notholithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*). One of the blocks at Challenge experienced a wildfire in 1961 and became part of a brushfield reclamation project (the “Penny Pines Program”) in which ponderosa pine was planted in the late 1960’s following pile and burn site preparation. The block was thinned in the early 1980’s. Soils at Challenge are classified as Sites loams (fine, parasequic, mesic Xeric Haplohumults) derived from metabasic rock (Adams et al. 2010). Site index for ponderosa pine is an estimated 34 m at age 50 (Zhang et al. 2006). Annual precipitation at Challenge averages 1730 mm, falling predominantly in the winter months. Average monthly temperatures range from 6 to 21° C (Adams et al. 2010).

The Whitmore site (40°37’N, 121°53’W; 760 m elevation) is located in the southern Cascades on private timberland in Shasta County near the town of Whitmore. The site was planted approximately 30 years prior to this study following mechanical site preparation and early chemical release from a shrub field induced by the stand-replacing Morelli Fire in 1968. Soils at Whitmore are classified as Aiken loams (clayey, oxidic, mesic Xeric Haplohumults) derived from andesitic lahar flows from the eruption of Mt. Lassen (Powers and Reynolds 1999). Average annual precipitation at Whitmore is 1140 mm, also concentrated during the winter months. Average annual precipitation at Whitmore is 1055 mm with average monthly temperatures ranging from 6 to 25°C. Site index for ponderosa pine is an estimated 23 m at age 50 (Powers and Reynolds 1999).

Climate at both sites is classified as Mediterranean with characteristic hot, dry summers and cool, wet winters.

Experimental Design

Four fuels treatments were applied at Whitmore in a randomized block design with four replications (n=4): mastication only (Mast/Only); mastication followed by herbicide (Mast/Herb); mastication followed by prescribed fire (Mast/Burn); and Control. Control and Mast/Burn treatments were implemented within 0.4 ha (54.9 × 73.8m) units, however, Mast/Only and Mast/Herb were implemented within smaller 0.2 ha (54.9 × 36.9m) units. At Whitmore, one or two tree plots (25.3 × 41.5 m) were nested within treatments to reduce edge effect. A total of 1,137 ponderosa pine trees were tagged at dbh (1.37 m) post-mastication during the summer of 2003 at Whitmore to investigate the effect of fuels treatment on tree and stand characteristics.

At Challenge, Mast/burn treatments within a randomized blocks design (n=4) were also used in addition to those at Whitmore in order to investigate the influence of crown scorch on subsequent growth of ponderosa pine. A total of 244 and 307 trees were tagged within the Mast/Burn units during the summer of 2005 at Challenge and the summer of 2006 at Whitmore to track mortality rates and growth over time.

Mastication was accomplished with a Rayco horizontal drum masticator with fixed teeth (Rayco Manufacturing Inc., Wooster, OH, US) during winter at Challenge and spring at Whitmore in 2002, with the exception of Mast/Burn units at Whitmore which were masticated May 2003. Mastication primarily targeted shrubs, but also small conifer and hardwood trees less than 15 cm dbh. The herbicide treatment was applied at Whitmore two years after mastication with a spring application of hexazinone (2.24 kg ai

ha⁻¹) and early summer application of tank-mixed glyphosate (4.48 kg ai ha⁻¹) and imazapyr (0.21 kg ai ha⁻¹) applied with a CO₂-pressurized backpack sprayer in 2004. Prescribed fire was conducted in 2005 at Challenge and 2006 at Whitmore during the month of June with strip-head fires spaced 2-3 m apart, although backing fire was also used to mitigate unacceptable fireline intensity (Knapp et al. 2012b). Conditions for all burns were low wind speeds (< 5 km h⁻¹) and relative humidity between 32 to 58% (Knapp et al. 2012b). Respective fuel moisture content for 1h, 10h, and 100h woody fuels prior to burns ranged between 5.4 to 14.8%, 8.8 to 17.6%, and 11.3 to 19.8% (Knapp et al. 2012b).

Data Collection

Trees measured during the summers of 2003 and 2014 at Whitmore were used to quantify changes in average tree growth across fuels treatments (11-year growth period). Additionally, measurements of crown base height and total height were taken on a randomly selected subset of 20 trees within each tree plot at Whitmore in order to calculate canopy base height (m), average live crown ratio (%), and average tree height (m) for each treatment. One replication of Mast/Only at Whitmore had no overstory pines and was therefore treated as a missing observation in all analyses.

To determine the effects of fire injuries on subsequent ponderosa pine growth, percent crown volume scorched was visually estimated within eight weeks of burning for surviving trees in the Mast/Burn treatments at both Challenge and Whitmore (Knapp et al. 2012b). Growth of fire-injured trees was calculated from initial post-fire dbh measurements in 2005 at Challenge and 2006 at Whitmore with subsequent remeasurement during the summer of 2013 (seven or eight years post-fire). Mortality of

ponderosa pine was surveyed annually for three years after prescribed burning and again during the summer of 2013 (seven or eight years post-fire).

Data Analyses

Tree and stand metrics were calculated from initial 2003 and 2014 values at Whitmore and compared among treatments. Missing dbh observations, largely in the Control units (47 of 69), were estimated using linear regression of 2003 and 2014 observations within each block-treatment combination ($p < 0.0001$, R^2 : 0.88-0.99, $n = 23-176$). Quadratic mean diameter increment (QMDinc; cm) of surviving trees was calculated based on QMD changes from 2003 and 2014 for each treated unit ($n = 4$; Mast/Only $n = 3$). Given the unbalanced design, a two-way General Linearized (GLM) ANOVA of least squares means was used to test treatment differences with respect to QMDinc, canopy base heights, mean total tree height, and live crown ratio among treatments. Due to small sample size ($n = 4$) we used a more liberal critical value ($\alpha = 0.10$) for multiple comparison tests to reduce likelihood of Type II error. Multiple comparison tests of least squares treatment means were tested using the Tukey-Kramer procedure (Sokal and Rohlf 1995).

Analysis of Covariance (ANCOVA) adjusted for initial dbh (cm) was used to determine the influence of fire injury in the form of crown volume scorched (CVS; $< 5\%$, 5-14%, 15-24%, 25-34%, 35-44%, 45-54%, 55-64%, 65-74%, 75-84%, and 85-100% categories) on seven or eight year ponderosa pine basal area increment (BAinc; $\text{cm}^2 \text{ tree}^{-1}$) at Whitmore and Challenge, respectively ($\alpha = 0.10$). The Tukey-Kramer method of multiple comparisons was used to determine differences in CVS levels with respect to mean BAinc adjusted for initial dbh (Sokal and Rohlf 1995).

Results

Treatment Effects on Ponderosa Pine Growth

Ponderosa pine stem growth and crown form eleven years following fuels treatment showed marked differences in comparison to the Control at Whitmore. Significant differences were found among fuels treatments with respect to QMD_{inc} ($F=59.26$, $d.f.=3$, $P<0.0001$). Average QMD_{inc} was significantly greater for all fuels treatments in comparison to Control, and Mast/Herb was significantly greater than Mast/Burn. Mast/Only did not differ significantly from either Mast/Herb or Mast/Burn with respect to QMD_{inc} (Table 3.1). Average tree heights in all masticated treatments were significantly greater than Control, however, masticated treatments did not differ ($F=19.99$, $d.f.=3$, $P=0.0004$) (Table 3.1, Fig. 3.1). Differences among treatments with respect to average canopy base height were non-significant ($F=2.37$, $d.f.=3$, $P=0.15$) (Table 3.1, Fig. 3.1). Average live crown ratio and QMD_{inc} were positively correlated ($r=0.9001$, $d.f.=14$, $P<0.0001$), however, all treatments were significantly different with respect to average live crown ratio in the descending order of Mast/Herb, Mast/Only, Mast/Burn, and Control ($F=106.07$, $d.f.=3$, $P<0.0001$) (Table 3.1).

Impact of Crown Scorch on Ponderosa Pine Growth

As expected, BA_{inc} was significantly related to initial dbh for ponderosa pine trees in the Mast/Burn treatments at both Challenge ($F=159.8$, $d.f.=1$, $P<0.0001$) and Whitmore ($F=374.2$, $d.f.=1$, $P<0.0001$). The ANCOVA assumption of homogeneous slopes was met based on non-significant interactions of CVS and initial dbh at both Challenge ($F=1.15$, $d.f.=9$, $P=0.33$) and Whitmore ($F=1.07$, $d.f.=9$, $P=0.38$). Levels of CVS (%) had a significant effect on resulting BA_{inc} adjusted for initial dbh at Whitmore

($F=3.54$, $d.f.=9$, $P<0.0004$), but not at Challenge ($F=1.61$, $d.f.=9$, $P=0.12$) (Fig. 3.2). At Whitmore, basal area growth of pines in the 25-34% CVS class was significantly greater than growth in all others except for the 15-24% and 35-44% CVS classes (Fig. 3.3).

Ponderosa Pine Mortality

Pine mortality differed across treatments and with time elapsed since treatment at the two northern California sites. Mortality at Whitmore was absent within Mast/Only and Mast/Herb, 0.06% in Control, and 8.2% within Mast/Burn. At Challenge, mortality within Mast/Burn was 34.7% (Table 3.2). Following the initial mortality (within three years following treatment; Knapp et al. 2012), there was no additional ponderosa pine mortality at Whitmore (year 7) and an additional 4.1% had died at Challenge (year 8).

Table 3.1 Ponderosa pine growth in response to fuels treatment at Whitmore.

Variable	Treatment				P-Value
	Control	Mast/Only	Mast/Burn	Mast/Herb	
QMD _{inc} (cm)	4.4 ^c	8.4 ^{ab}	8.0 ^b	9.1 ^a	<0.0001
Mean Tree Height (m)	11.17 ^b	15.57 ^a	14.53 ^a	15.80 ^a	0.0004
Crown Ratio	0.60 ^d	0.71 ^b	0.67 ^c	0.76 ^a	<0.0001
Canopy Base Height	4.30	4.46	4.71	3.89	0.146

Note: Unique superscript letters represent significant differences determined by Tukey-Kramer multiple comparisons at $\alpha=0.10$.

Table 3.2 Ponderosa pine mortality rates from 2003 to 2014 by treatment at Whitmore and mortality rates from 2005 to 2014 at Challenge.

Variable	Treatment			
	Control	Mast/Only	Mast/Burn	Mast/Herb
Whitmore Mortality (%)	0.6 (0.9)	0	8.2 (4.7)	0
Challenge Mortality (%)	-	-	34.7 (17.2)	-

Note: Standard error is shown in parentheses and dashes (-) signify absence of data.

Table 3.3 Quadratic mean diameter, stocking, and stocking density by treatment at Whitmore in 2003 and 2014.

Variable	Year	Treatment			
		Control	Mast/Only	Mast/Burn	Mast/Herb
Quadratic Mean Diameter (cm)	2003	14.7 (0.7)	19.0 (0.7)	18.0 (0.4)	19.5 (1.2)
	2014	19.1 (0.9)	27.2 (1.2)	26.0 (0.5)	28.7 (1.0)
Plot Basal Area (m ² ha ⁻¹)	2003	12.3 (1.5)	9.3 (1.3)	9.9 (0.9)	9.7 (1.2)
	2014	20.6 (2.0)	19.0 (2.5)	20.6 (1.6)	20.9 (1.6)
Tree Density (trees ha ⁻¹)	2003	725.9 (60.1)	336.9 (71.9)	422.0 (27.0)	324.2 (24.3)
	2014	721.1 (59.7)	336.9 (71.9)	388.6 (30.9)	324.2 (24.3)

Note: Standard error is shown in parentheses.

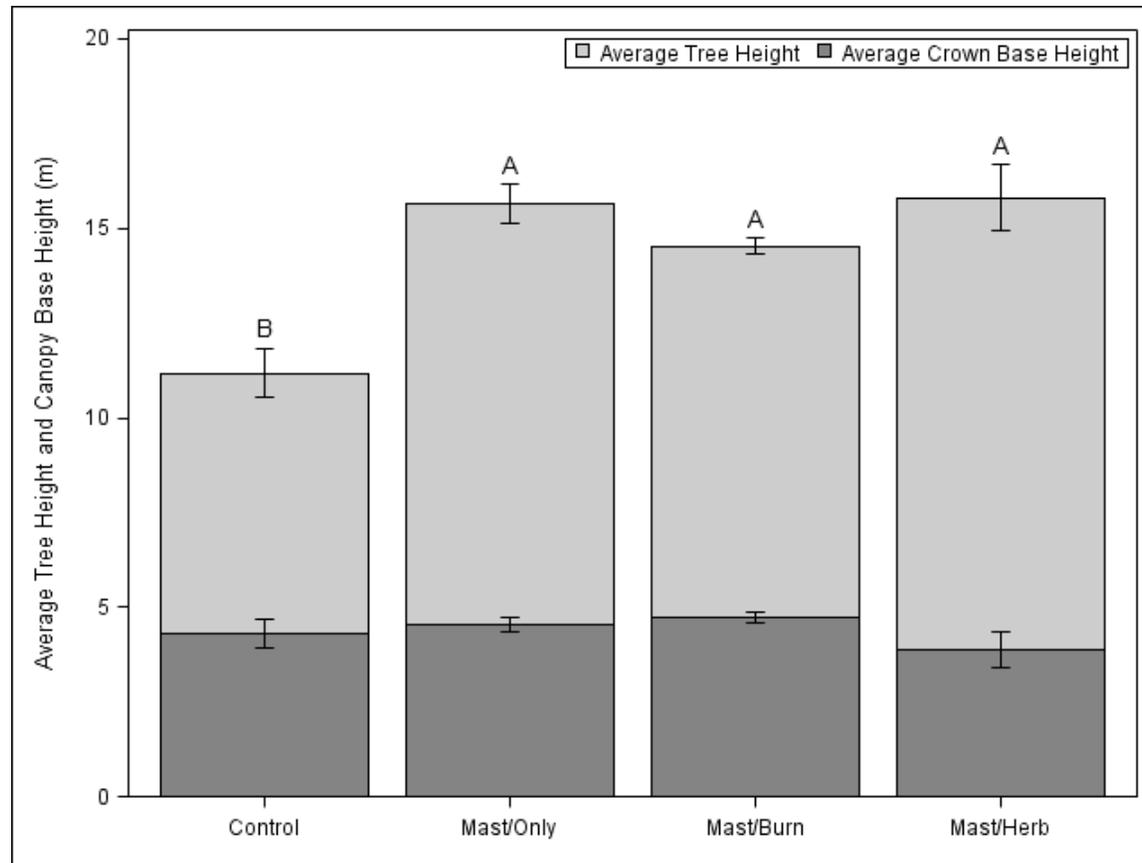


Figure 3.1 Average tree height and canopy base height by treatment at Whitmore.

Note: Bars represent standard errors. Unique letters indicate significant differences detected by Tukey-Kramer multiple comparison tests of least squares means for average total tree height. Canopy base height did not differ significantly among treatments ($\alpha=0.10$).

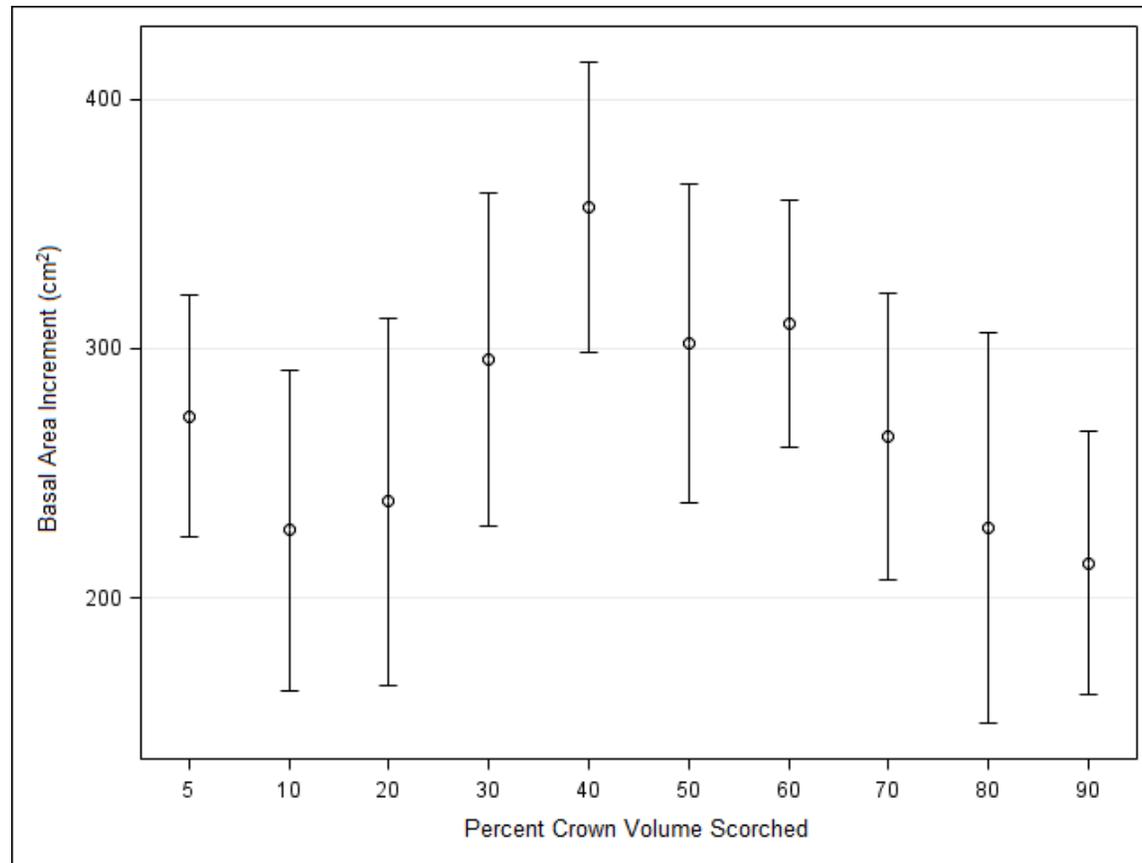


Figure 3.2 Relationship between basal area increment adjusted for initial dbh and levels of percent crown volume scorched for ponderosa pines at Challenge.

Note: Bars represent 90% confidence intervals. No significant differences were detected by Tukey-Kramer multiple comparison tests of least squares means ($\alpha=0.10$).

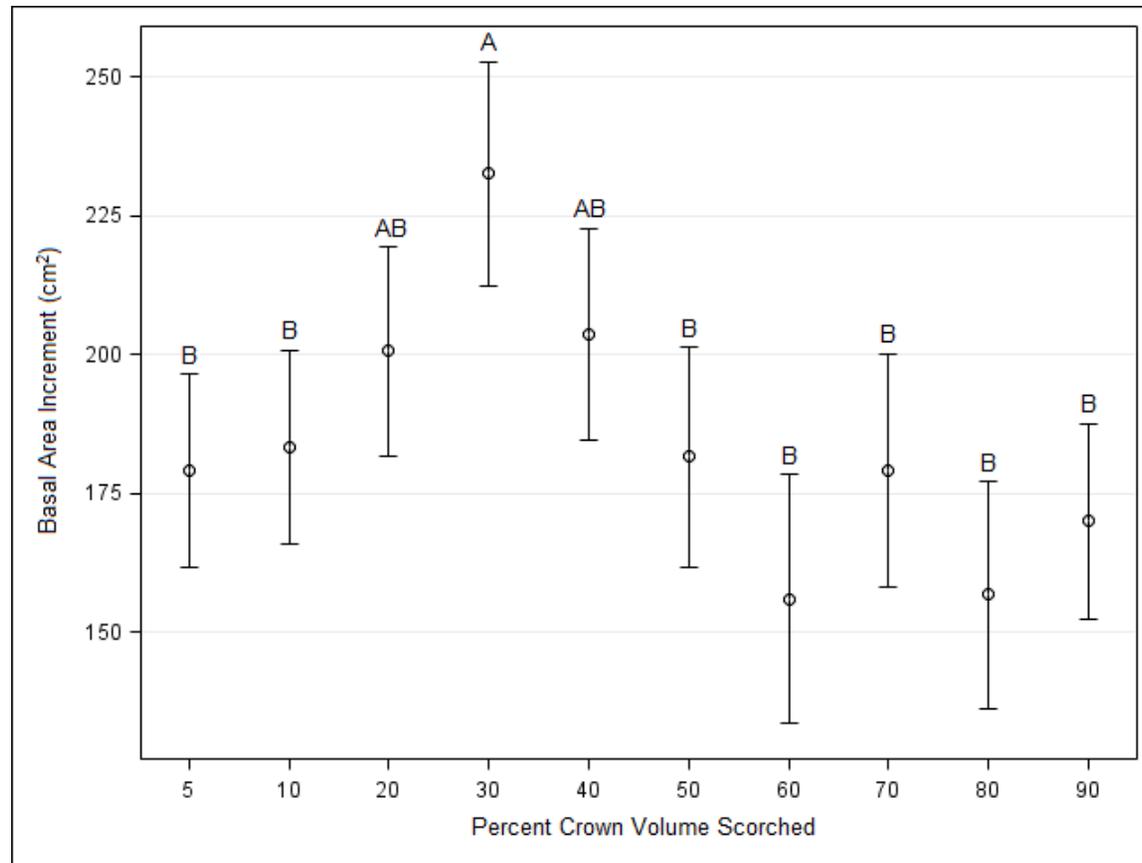


Figure 3.3 Relationship between basal area increment adjusted for initial dbh and levels of percent crown volume scorched for ponderosa pines at Whitmore.

Note: Bars represent 90% confidence intervals. Unique letters indicate significant differences detected by Tukey-Kramer multiple comparison tests of least squares means ($\alpha=0.10$).

Discussion

Fuels Treatments and Overstory Growth

This study demonstrated that ponderosa pine growth was stimulated by mastication and associated fuels treatments. In the Mast/Only treatments, QMD $_{inc}$ was nearly double that of the Control. Both low-thinning of small diameter pines and removal of non-sprouting *Arctostaphylos* shrubs likely increased scarce water resources critical during stand development at Whitmore (Powers and Reynolds 1999). Increased diameter growth following mastication is consistent with other studies involving competing vegetation control (McDonald and Fiddler 1993, Zhang et al. 2013) and thinning in ponderosa pine (Sala et al. 2005, Skov et al. 2005, Busse et al. 2009, Stephens et al. 2012).

Surprisingly, broadcast applications of hexazinone (2.24 kg ai ha⁻¹) and tank-mixed glyphosate (4.48 kg ai ha⁻¹) and imazapyr (0.21 kg ai ha⁻¹) in the Mast/Herb treatment failed to significantly increase radial growth in comparison to Mast/Only over the 11 year period even though shrub competition was considerably reduced (Chapter 2, Table 2.1). The dominant competing species at Whitmore following mastication was poison-oak (*T. diversilobum*), but was likely a weak competitor with the well-established pines. It may be that longer-term monitoring of tree growth may reveal benefits from herbicide application. Greater radial growth rates of Mast/Herb versus those of Mast/Burn were likely due to positive effects of chemical competition control in Mast/Herb combined with negative effects of fire injuries in Mast/Burn, although both treatment effects were non-significant in comparison to Mast/Only.

Non-significant differences in radial growth between Mast/Burn and Mast/Only treatments could have resulted from compensatory effects of burning such as nutrient release, fire-induced overstory thinning (Table 3.3), or further reduction of understory competition. Kennedy Sutherland et al. (1991) found ponderosa pine growth rates in northern Arizona recovered to unburned levels after only 2 years following prescribed burning. Similarly, Sala et al. (2005) found no difference between thinning alone and thinning with prescribed burning treatments over 8 and 9 years. Average live crown ratio indicates the photosynthetic capacity of an individual and can be influenced both directly and indirectly by treatment. The positive correlation between crown ratios and radial growth (*QMD_{inc}*) across treatments and the significant differences found among all treatments with respect to crown ratio may be indicative of the stress due to competition.

Although many studies have found elevated canopy base heights following thinning and still others have found an additional increase with subsequent prescribed burning (Schwilk et al. 2009a, Stephens et al. 2009), the absence of significant treatment differences in our study was possibly due to a loss of treatment effect over time. Owing to a lack of immediate post-treatment data on canopy base heights we can only speculate that initial treatment differences likely existed. Subsequent crown development and canopy closure may have prevented a lasting effect of prescribed fire on canopy base height through the process of self-pruning. Greater mean tree height found in all fuels treatments relative to Control is largely a product of the low thinning carried out by mastication. Height of ponderosa pine in the control units, however, were largely reduced overall in comparison to treated individuals and this disparity largely reflects the intense competition among pines and *Arctostaphylos* shrubs which is consistent with

other studies on competing vegetation control in ponderosa pine plantations (McDonald and Fiddler 1993, Powers and Reynolds 1999). Taller trees resulting from fuels treatments indicate an overstory more resilient to crown scorch in the event of wildfire since smaller trees, lower to the flaming front, have a higher probability of excessive crown scorch (Van Wagner 1977, Keyes and O'Hara 2002, Agee and Skinner 2005).

Effects of Prescribed Fire and Mastication

Beyond an initial pulse of post-fire mortality, results from this study suggest substantial resilience of ponderosa pine to the combined effects of mastication and prescribed fire. Initial mortality following the Mast/Burn treatment was minimal at Whitmore but more pronounced at Challenge, which was largely attributed to excessive mortality within only one of the units (Knapp et al. 2012b). A negative linear relationship was expected to exist between CVS and resulting *BA_{inc}*, however, both sites exhibited increased growth at moderate levels of crown volume scorched (Fig. 3.2 and 3.3). Since methods of this study did not account for competitive effects of neighboring trees and shrubs, a plausible explanation for unexpected trends in *BA_{inc}* among CVS levels exists. Kauffman and Martin (1990) looked at the response of various shrub species in mixed-conifer forests of the Sierras and found that greater levels of fuel consumption and lethal heating largely determined shrub survival following prescribed fire. Although speculative, moderate levels of CVS may reflect fireline intensity beneficial in terms of reducing surrounding competition without inflicting substantial tree injury. Individuals receiving the lowest levels of CVS/fire intensity would, ostensibly, not receive the benefit of competitive release, whereas levels of CVS surpassing a 40-50% threshold led to declines in growth to be expected from fire injury. In addition,

lower branches closer to the flaming front receive less available light and their contribution to photosynthesis and radial growth are far less than that of the upper crown (Roberts 1994, Protz et al. 2000). Moderate levels of crown volume scorch were, therefore, less likely to damage tissue contributing substantial carbohydrates to future growth.

Lastly, our results suggest that CVS exceeding 40-50% had a more lasting impact on the smaller-sized ponderosa pine at Whitmore in contrast to the larger pines at Challenge, for which the relationships among CVS levels and adjusted BA_{inc} were non-significant (Fig. 3.3). These subtle or non-existent effects of post-mastication prescribed fire support a growing body of research on the latent resilience of ponderosa pine forests to intensive fuels treatments (Skov et al. 2004, Sala et al. 2005, Larson et al. 2013).

Management Implications

Results of this study provide important implications for fuels treatment in fire-prone ponderosa pine forests. Highly flammable sclerophyllous shrub communities (e.g. *Arctostaphylos* and *Ceanothus spp.*) are notorious for colonization and persistence following stand-replacement within coniferous forests of northern California (McDonald and Fiddler 1993, Zhang et al. 2013). Mechanical mastication alone or used in conjunction with herbicide or prescribed fire can accelerate tree growth providing for a more fire-resistant overstory which may inhibit future ladder fuel establishment and growth.

At Whitmore, herbicide application following mastication did not produce significant increases in radial growth over mastication alone. Studies of competition control for ponderosa pine in this region consistently acknowledge that benefits are best

captured during the early stages of stand development (Busse et al. 1996, Powers and Reynolds 1999, Zhang et al. 2013). Mastication treatments not only removed competing vegetation, but also thinned overstory individuals which liberated growing space for residual overstory as well as competing hardwoods. Despite a ~50% reduction in overstory stocking density and ~20% reduction in basal area following mastication (Table 3.3), the stage of stand development and absence of problematic resprouting shrubs likely precluded the necessity for subsequent herbicide treatment at Whitmore. The non-sprouting shrubs *Arctostaphylos viscida* and *A. manzanita* competed vigorously with pines in the Control, however, these shade-intolerant species were effectively excluded by initial mastication and subsequent canopy development.

Prescribed burning is generally recognized as an ideal component of any fuels treatment since surface fuels and ground fuels are consumed and vital ecosystem processes which may increase understory biodiversity are reestablished (Brockway and Lewis 1997, Kane et al. 2010, Webster and Halpern 2010, Ryan et al. 2013). In addition, wildfire-induced mortality has been projected to be higher in masticated stands which have not received subsequent prescribed burning, further supporting the need for prescribed fire following mastication (Kobziar et al. 2009, Knapp et al. 2012b, Reiner et al. 2012). Results of this study demonstrate the feasibility of prescribed burning in masticated stands without lasting consequences for overstory ponderosa pine growth. Fire-induced overstory mortality was minimal at Whitmore, however, high mortality rates in one unit at Challenge suggest higher fuel loading of masticated residues may pose issues for reintroduction of prescribed fire where overstory conifers are present (Knapp et al. 2012b). The primary research on the effects of mastication followed by prescribed

fire has been in northern California; research in other ecosystems where these treatments are widely used is needed to illuminate more general tree growth and mortality responses.

Mastication alters fuels and results in somewhat novel fire behavior (Knapp et al. 2012b, Kreye et al. 2014). The compactness of these woody fuel beds results in longer residence times and smoldering durations (Busse et al. 2010, Knapp et al. 2012b). In addition, prescribed fires have resulted in greater crown scorch than modeled predictions ($1.8 \times$ BehavePlus predictions; Knapp et al. 2012b). Prescribed burning of masticated fuels should be conducted when soil moisture prevents lethal heating to soil and roots (Busse et al. 2010). Burning with low air temperatures or greater wind speeds may diffuse convective heating to overstory foliage (Van Wagner 1973, Kobziar et al. 2009, Knapp et al. 2012b). Differences in overstory mortality between Whitmore and Challenge were likely a function of pre-fire fuel loading for which Whitmore and Challenge represent the low and high ends of the regional spectrum (Kane et al. 2009, Knapp et al. 2012b). Additionally, ignition pattern potentially affected overstory mortality since the majority of mortality at Challenge resulted from igniting via strip-head fires within one experimental unit which proved too aggressive given the topography (12° slope) and fuel loading (Knapp et al. 2012b).

Mastication is also an effective tool to expedite tree growth in planted stands of ponderosa pine suffering from severe hardwood competition. Subsequent herbicide application may not be justifiable if sprouting or shade tolerant shrubs are not abundant and sufficient canopy cover is present to deter intolerant, non-sprouting species (e.g. *Arctostaphylos viscida*). Prescribed fire following mastication can increase treatment effectiveness by consuming ground and surface fuels (Kane et al. 2010) without a lasting

impact on overstory ponderosa pine. An increased focus on additional species and development of burning prescriptions will help clarify how we might realize the combined benefits of mastication and prescribed fire across fire-prone forests.

CHAPTER IV

CONCLUSION

Past land use practices and federal fire suppression have increased hazardous fuels within ponderosa pine forests in the western United States (Agee 1998, Brown et al. 2004). These widespread conditions have prompted extensive fuels treatments including mechanical mastication which reduces ladder fuels to a compact layer of mulched residues. This study addressed two poorly understood aspects of mechanical mastication in ponderosa pine forests of northern California. First, what factors influence the long-term (10 or 11 year) recovery of ladder fuels and surface fuels following mastication and mastication with subsequent herbicide application or prescribed fire? Second, what is the influence of mastication and mastication with subsequent herbicide or prescribed fire on long-term ponderosa pine growth and mortality?

Response of woody vegetation to mastication and mastication with subsequent herbicide or prescribed fire was not only dependent on the method of maintenance, but also site-specific factors including productivity, species assemblage, and overstory dynamics. In general, herbicide proved to be an effective tool for mitigating shrub and small tree response following mastication, whereas prescribed fire had mixed effects on woody vegetation response and was largely affected by the presence of overstory trees. Surface fuels were not mitigated by prescribed fire over the long-term, suggesting the need for repeated prescribed fire entries in order to manage the continuous accretion of

surface fuels in these ponderosa pine forests. Species richness of woody shrubs was enhanced by subsequent prescribed fire at the more productive and biodiverse site in the northern Sierras (Challenge), but was minimally affected in the southern Cascades (Whitmore).

Overstory ponderosa pine were released from severe shrub competition 10 or 11 years following mastication in the southern Cascades (Whitmore). Mastication resulted in significantly greater average radial growth and average total tree height in comparison to control. However, neither prescribed fire nor herbicide application following mastication significantly altered average radial growth of ponderosa pine tree in comparison to mastication alone and canopy base heights did not differ significantly among treatments. Radial growth of surviving ponderosa pine was largely unaffected by the amount of crown volume scorched, although fire intensities resulting in moderate crown scorch may have provided some benefits to overstory pines not accounted for in this study. Mortality rates were substantial (34.7%) in the northern Sierras (Challenge) compared to the southern Cascades (8.2%). Higher mortality at Challenge was attributed to higher surface fuel loading leading to long residence times and excessive crown scorch (Knapp et al. 2012b).

Mechanical mastication is capable of providing the dual benefits of releasing overstory ponderosa pine while simultaneously mitigating ladder fuels. These benefits are clearly interdependent since reducing shrub and small tree competition liberates resources for overstory growth (Powers and Reynolds 1999, Zhang et al. 2006). Herbicide application following mastication proved most effective in both reducing ladder fuels and stimulating tree growth over the long-term. However, considerations for

understory biodiversity and ecological succession may take precedence over the potential gains from chemical vegetation control (Brockway and Outcalt 2000, Freeman and Jose 2009). Prescribed fire effectively reduced ladder fuel recovery following mastication when overstory trees were present. Correspondingly, overstory mortality of ponderosa pine following prescribed burning is likely to cause lasting negative consequences for the longevity of mechanical mastication in this region. More research is needed to refine our understanding of prescribed fire and herbicides as maintenance methods for mechanical treatments including mechanical mastication.

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