Project Title: Longevity and Effectiveness of Mechanical Mastication Treatments

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I. Abstract

This report summarizes research funded by the Joint Fire Science Program (JFSP Project Number 12-1-03-31) addressing needs for information regarding the effectiveness and longevity of fuels treatments. We investigated the longevity of effects associated with mastication treatments on variables including fuels, vegetation, and fire behavior in northern California and southern Oregon. We coordinated a synthesis of the effects of mastication on fire behavior; emergent findings and pressing needs were highlighted. In a large field study, we measured the effects of time-since-mastication on fuelbed properties. Masticated fuels decomposed and compressed over time across sites, with the greatest reductions in fine fuels (1-hr and 10-hr). In a subset of those plots, we measured laboratory fire behavior across a time-since-mastication chronosequence, highlighting reductions in fire intensity over time, but with increased smoldering combustion. We used the large plot network to evaluate shrub diversity, height, and cover responses to treatments. Vegetation height and cover was greatest in sites dominated by resprouting shrubs and trees. At two sites where we had longitudinal data on fuels and vegetation, we measured shrub and ladder fuel responses in relation to residual overstory produced through a range of fuels treatments. Treatment longevity was linked to supplemental treatments such as herbicide or prescribed fire. In those same sites, we measured overstory pine growth and longer-term mortality from treatments, including prescribed fire applied following mastication. Results highlight that of ponderosa pines that survive post-mastication prescribed fire, growth was best in cases with intermediate scorch. Collectively, the results generated in this study will enhance the information available to land mangers regarding the viability of masticating fuels across the region and more broadly how these fuels treatments maintain effectiveness and longevity.

II. Background and Purpose

Mechanical mastication is an increasingly common fuels management treatment in fire-prone forests and rangelands across the US. Mastication is commonly used in fuelbreaks and along the wildland-urban interface, often in lieu of prescribed fire or other mechanical treatments (Agee and Skinner 2005, Vitorelo et al. 2009, Potts et al. 2010, Kreye et al. 2014a). By reducing vertical fuels to a compact woody fuelbed, mastication allows improved firefighter access for fire suppression and can make subsequent prescribed fires easier to implement (Knapp et al. 2012, Kreye et al. 2014a).

What we know about the effects of mastication pales in comparison to what we don't: 1) the effects of time since treatment on vegetation recovery (in this region, primarily shrub re-growth); 2) changes in fuelbed characteristics over time (load, bulk density, fuelbed depth, particle density); and 3) the fundamental effects of fuelbed aging on potential fire behavior. All three of these information gaps play a role in treatment effectiveness – the probability of modifying fire behavior and effects over the untreated condition. Providing useful metrics that rapidly assess how these fuels vary over time with respect to mitigating fire behavior will enable land managers to make more educated decisions about where and when to use mechanical mastication as a fuel treatment tool.

Although mastication has become an increasingly common method to treat fuels in fire-prone forests of the western US, prior research has not addressed long-term treatment effectiveness. Both high initial treatment costs (Vitorelo et al. 2009) and concerns over the rapid reestablishment of shrubs, particularly resprouting species (Kane et al. 2010) prompted this research on fuels treatment longevity of mastication. Furthermore, we sought to address the potential use of maintenance treatments (i.e. herbicides or prescribed fire) following mastication and their effects on both overstory trees, and live and dead surface fuels.

There are several reasons why mastication is a common fuels treatment. Unlike prescribed fire, mechanical mastication generates no smoke, is less restricted by weather and climatic variation, and can be performed in areas difficult for prescribed fire use (i.e. WUI and in areas where potential fire behavior is prohibitive). Mastication can be scheduled easily (few restrictions other than *Activity Level* limitations) and can be used on a variety of vegetation types and slopes (Vitorelo et al. 2009). Mastication effectively eliminates vertical fuelbed continuity and creates a compact surface fuelbed (Kane et al. 2009, Battaglia et al. 2010, Reiner et al. 2010, Kreye et al. 2014a), which can slow vegetation recovery (Kane et al. 2010, Potts et al. 2010) and dampen the rate of fire spread and its intensity (Glitzenstein et al. 2006, Knapp et al. 2012, Kreye et al. 2014a).

Despite its advantages, there are some drawbacks to the use of mastication. Mechanical mastication substantially increases dead surface woody fuel loading because generated fuels are retained on site. The increased surface fuelbed bulk density may lead to long-duration smoldering fires (Busse et al. 2005, Busse et al. 2010, Kreye et al. 2011) and substantial canopy scorch and tree mortality during prescribed fires (Bradley et al. 2006, Kobziar et al. 2009, Reiner et al. 2010, Knapp et al. 2012) or wildfires. In other cases, masticated shrubs may vigorously resprout (Kane et al. 2010, Potts et al. 2010), resulting in regrowth of shrub fuels prior to decomposition of the heavy surface woody fuelbed generated by mastication (Figure 1). This "dual threat" has the potential to exacerbate fire intensity and severity because the added surface fuels may 1) increase the likelihood that shrubs will be preheated and burn under a broader range of live fuel moisture conditions and 2) generate long-duration heating that increases fire severity (Knapp et al. 2012). It is therefore critical to understand the rate of surface fuel decomposition and fuelbed changes in relation to the rate of live fuel regrowth. These relationships are likely to vary with several environmental and ecological scenarios, highlighting important pre- and post-treatment characteristics that deserve management attention.

To push the science forward, we capitalized on data collected in northern California and southwest Oregon during our previously funded JFSP project (Knapp et al. 05-2-1-20) and added additional masticated sites in the region. Using sites masticated from November 2002 to May 2005 and intensively sampled between 2005 and 2006 (Kane et al. 2009), we evaluated the changes in woody fuelbed structure (loading, bulk density, particle density, fuelbed depth) and above-ground vegetation recovery (cover, height, and diversity) ca. a decade after mastication. We coupled this intensive study with additional sites spanning the geographic and compositional variation present in the region.

◄*Figure 1.* Rapid live fuel recovery of *Ceanothus velutinus* in the Klamath Mountains of California ***only 14 months following mechanical mastication***. In addition to the live fuel (ca. 0.75 m tall), the 5 cm deep dead masticated fuelbed beneath contained 43.2 Mg ha^{-1} of woody fuel (26.5 Mg ha^{-1} in the finer 1- and 10-hour fuels, collectively).

An area of mastication research that is vastly under-studied is work related to understanding fire behavior in these fuelbeds (Glitzenstein et al. 2006, Kobziar et al. 2009, Reiner et al. 2010, Kreye et al. 2011). In our previous work, we measured fire behavior in a laboratory setting (Kreye et al. 2011), in small field mesocosms (Busse et al., 2010), and in field prescribed burns (Knapp et al. 2012); the combined understanding had several holes, underscoring the pressing management and research needs. In this project we used additional laboratory burning of woody fuelbeds across a time-since-treatment chronosequence (Kreye et al. 2016a), and coordinated a state-of-the-science review on fire behavior in masticated fuels (Kreye et al. 2014a) and a regional synthesis for ecological effects (Kreye et al. 2016b). These contributions form a broader dataset to aid the development of future fuel models for masticated fuelbeds.

Projects such as the Smoke Modeling Intercomparison Project (SEMIP; Larkin et al. 2012) and Interagency Fuels Treatment Decision Support System (IFTDSS; Drury et al. 2016) have indicated the importance of providing project data in formats useful to researchers and land managers. In this project, the broader dataset we are providing plus any updated fuel models and associated model runs are available on a project website: http://www.fs.fed.us/psw/topics/fire_science/masticated_fuels/. We are currently working with the IFTDSS Version 3 development team to ensure that our data and models will be compatible with IFTDSS when the new system becomes operational.

Lastly, given the increased interest in mastication from both managers and scientists, we developed an annotated bibliography for use by both managers and scientists interested in mastication's effects on fuels, vegetation, and fire behavior. We see this bibliography as a first step to synthesizing the knowledge and needs for mastication research and application.

III. Study Descriptions and Locations

This large study had several phases and was investigated at different scales. Each study is listed below, with relevant methods and findings.

Fuelbed Responses Study

Study Sites and Locations

We selected 25 masticated fuel treatments in the Sierra Nevada, southern Cascades, North Coast Ranges, and Klamath Mountains of northern California and southern Oregon (Table 1). Sites were selected from treatment maps provided by regional forest managers and ranged from 1 to 16 years since treatment. Seven of the 25 sites measured were previously sampled 8 or 9 years prior by Kane et al. (2009) and remeasured to compare changes in fuel loading, depth, size class composition (1-, 10-, 100 and 1000-hour), and fuel particle specific gravity.

In general, sites are characterized by a Mediterranean climate, with cool, wet winters and hot, dry summers. Elevation across the 25 sites ranged from 237 to 2083 m above sea level and average annual precipitation ranged from 648 to 1752 mm (PRISM Climate Group 2004). The vegetation was highly variable spanning montane chaparral ecosystems, oak woodlands, pine-dominated and mixed-conifer forests.

Study Methods

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

In the lab, fuels from each plot were sorted into standard timelag diameter classes (1-hour, < 0.625 cm; 10-hour, 0.625 to 2.54 cm; 100-hour, 2.55 to 7.62 cm). Due to the irregular shape of masticated material, the timelag size was classified as in Kane et al. (2009). All sorted fuels were oven-dried at 85° C until no further weight loss occurred (≥ 72 hours) and weighed to estimate dry weight.

In addition to changes in fuel loading, specific gravity (analogous to particle density; Sackett 1980) was measured on three masticated woody pieces from each timelag class (1-hour, 10-hour, and 100-hour) and plot (n = up to 45 from a site per size class; not all plots had particles in all size classes).

Data Analyses

Total fuel loading and average loading for each fuel particle size (1-, 10-, and 100-hour woody, duff, and litter) were compared across sites. Simple linear regression analysis was used to determine the relationships between fuel loading and fuelbed depth to time-since-mastication. Within this analysis, site averages (n=23) were used as replicates. Changes in fuel particle specific gravity, fuel loading (by timelag category, as above), and fuel depth were compared among the seven sites using one-tailed t-tests for 1-, 10- and 100-hour fuels because one direction of change (i.e. a reduction) was assumed due to decomposition. For litter and duff, a two-tailed t-test was used based on the assumption that additional inputs occurred since treatment, maintaining the possibility of detecting changes in two directions (inputs vs. losses due to decomposition).

Table 1. Description of masticated study sites in northern California and southern Oregon. Identification numbers are arranged from north to south.

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

Vegetation Response studies

Study Sites and Locations

We used the same 25 sites for sampling shrub response across a time-since-treatment, annual precipitation, fuelbed depth, and canopy closure gradient. At two additional sites (Challenge in the northern Sierra Nevada and Whitmore in the southern Cascade Range), we used our previous data (Kane et al. 2010) on vegetation response following mastication and subsequent maintenance treatments (mastication plus herbicides, mastication plus prescribed fire, and mastication alone) to evaluate long-term (ca. decade) responses to these treatments. The Challenge site was located at 850 m in elevation and receives on average 1730 mm of annual precipitation. The Whitmore site was located at 760 m in elevation, receiving an average of 1055 mm of annual precipitation.

At Challenge and Whitmore, we followed our original censuses of tree mortality (Knapp et al. 2012) with a long-term analysis of radial growth, height (crown and total), additional mortality, and stand structure. We compared these data across treatments and focused on the responses of ponderosa pines to the combined effects of mastication and prescribed fire.

Extensive response of vegetation (2014)

At each of the 25 sites in northern California and southern Oregon, 13-15 circular plots (3 m radius) were randomly located (as described for *Fuelbed Responses Study*). Plots were sub-divided into four quadrants in which average height and cover were measure separately for each woody species. In addition, a convex densiometer was used to estimate canopy closure as an average of four measurements taken at cardinal directions from each plot center.

Intensive response of vegetation (2013)

Woody vegetation response was sampled within each of four treatments applied in a randomized complete block design at the Challenge and Whitmore sites. The treatments mastication only, mastication with prescribed fire (~3 years post-mastication), mastication and herbicide (hexazinone and tank-mixed glyphosate and imazapyr; ~2 years post-mastication), and a no treatment control were replicated four times (four blocks). Shrub and small tree species were sampled for height, basal diameter (or % cover for infeasible species), and stem density within five or ten systematically placed 1 m × 10 m belt transects per treatment. In addition, measurements of canopy openness and overstory basal area taken at each transect midpoint were used to detect the influence of residual overstory on woody vegetation response within the mastication and prescribed fire treatments.

Response of overstory trees

Diameter at breast height, height, and height to live crown base were measured on overstory ponderosa pines within the above treatments during the summer of 2014 at the

Whitmore site. Dbh measurements from 2003 (immediate post-mastication) and 2014 were used to compare potential differences in quadratic mean diameter increment (QMD_{inc}). Measurements from 2014 were used to estimate average tree height, average canopy base height, and average crown ratio among treatments. We investigated individual ponderosa pine growth (seven or eight year basal area increment) as a response to percent crown volume scorched following mastication and prescribed fire at both the Challenge and Whitmore sites. Dbh and scorch measurements were taken immediately post-fire (2005 or 2006) and dbh was measured again during the summer of 2013.

Data Analysis

Extensive response of vegetation sites

Both shrub cover and average height were compared among the 25 masticated sites using an analysis of variance and Tukey-Kramer HSD tests for multiple comparisons of site averages. Linear regressions were used to determine the effect of time since treatment on both the cover and average height of shrubs across study sites. Stepwise linear regression was used to explore the potential influence of mean annual precipitation, average fuel bed depth, and average canopy closure, in addition to time since treatment, on average shrub height and cover across sites.

Shrub species encountered in our sampling were classified by their dominant reproductive strategy (i.e. resprouting or obligate seeding) in order to assess the influence or mastication on the regeneration dynamics of woody species at each site. Within each site average height of resprouting and obligate seeding species were compared using a two-sided t-test.

Intensive response of vegetation sites

Woody vegetation response (basal area, stem density, average stem height, cover, and species richness) was compared among treatments using a two-way General Linear Model (GLM) ANOVA. Multiple comparisons of treatment means were tested using Fisher's Least Significant Difference (LSD) test. Gap Light Analyzer Version 2.0 was used to compute canopy openness for each gridpoint (Frazer et al. 1999). Simple linear regression was used to explore potential relationships between canopy openness (%) or overstory basal area (m^2 ha^{-1}) and total shrub and small tree basal area (m^2 ha^{-1}) for the mastication and prescribed burning treatments at both Challenge and Whitmore.

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. Rare species occurring in less than 5% of transects were removed from analysis. Since species abundance was measured using both basal area and cover, data were relativized by the maximum values within treatment groups for analysis. If blocked MRPP results confirmed significant treatment differences in species composition, a blocked indicator species analysis (ISA) was used to determine species-treatment relationships. Statistical significance of independent variables was determined using Monte Carlo tests with 5000 randomizations.

One replication of mastication only at Whitmore had few overstory pines and was therefore treated as a missing observation in all analyses comparing treatments. Quadratic mean diameter increment (QMD*inc*; cm) was calculated for each treated unit (n=4; Mast/Only n=3) based on QMD increases from 2003 to 2014 of all surviving trees. Given the unbalanced design, a two-way GLM ANOVA using least squares means was used to test treatment differences with respect to average QMD*inc*, canopy base heights, total tree height, and live crown ratio among treatments.

Analysis of Covariance (ANCOVA) adjusted for initial dbh was used to determine the influence of crown scorch (<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 increment of ponderosa pine basal area (BA*inc*; cm^2 $tree^{-1}$) at Whitmore and Challenge, respectively. The Tukey-Kramer method of multiple comparisons was used to determine differences in scorch levels with respect to mean BA*inc* adjusted for initial dbh. Status of overstory pines was tracked within each mastication and prescribed fire unit and averaged at each site for mortality one month, one year, two years, three years, and seven or eight years post-fire.

Laboratory Fire Behavior study

Fuel collection locations

To evaluate how fire behavior changes with fuelbed decay, we selected four sites from the full list that had similar vegetation and climate, but were masticated 2 to 16 years before fuels were collected. Mastication treatments were conducted in 2012 (Six Rivers National Forest, California), 2010 (Shasta-Trinity National Forest, California), 2004 (Shasta-Trinity National Forest), and 1998 (Applegate Valley, Bureau of Land Management, Oregon). All sites are located within the Klamath Mountains/California High Coast Range level III ecoregion (U.S. EPA, 2013). Although overstory conditions varied, the midstory vegetation that was targeted for mastication was dominated by *Arctostaphylos* spp. and *Ceanothus* spp. shrubs at all sites. Composition of masticated woody debris (i.e. proportion by size class) and specific gravity of masticated particles were evaluated across these sites by Reed (2016; Fuelbed response study).

Experimental burning

Collected woody fuels were used to create laboratory-scale (25 cm × 25 cm) fuelbeds for burning experiments. Detailed methods for fuel size proportions, apparatus instructions, and experimental measurements are found in Kreye et al. (2016a).

Fuelbeds were burned within combustion boxes lined with thick cement board along the bottom and sides. For each site, fuelbeds were created with three fuel load treatments:

156, 313, and 469 g of fuel corresponding to total loads of 25, 50, 75 Mg ha^{-1}, respectively. Composition of fuel size classes (1-hour and 10-hour) differed across fuelbed age to reflect changes observed in field; proportions of 1-hour fuels were reduced in older sites. Bulk density (kg m^{-3}) of fuelbeds was calculated from fuelbed depth and total fuel mass. Fuels were at laboratory moisture conditions (5.9 ± 0.6% gravimetric moisture content across all fuel sizes, based on 22 random samples) when burned. Experiments were replicated three times within each fuel load and fuelbed age combination, for a total of 36 burns.

Fuelbeds were ignited following methods in Kreye et al. (2011). During burn experiments, we recorded maximum flame height (cm), observed against a vertically oriented ruler; flaming time (s, time elapsed from ignition to flame extinction); and smoldering time (s, time elapsed from the end of flaming to the end of glowing combustion that was visible under darkened conditions). Following smoldering combustion, we weighed the remaining fuel mass and calculated percent consumption. To estimate energy release, burns were conducted on top of a bench scale connected to a computer and weight was recorded throughout burning at 5 second intervals. Energy release was calculated as fireline intensity (kW m^{-1}) by multiplying mass loss (g) per 5 s interval multiplied by a representative heat content (19.2 kJ g^{-1}, Countryman 1982) divided by the width (0.25 m) of the fuelbed, as described in Kreye et al. (2011).

Data analysis

Fire behavior metrics (peak fireline intensity, flame height, flaming duration, smoldering duration, and fuel consumption) were each compared across fuelbed age and total fuel load category (25, 50, 75 Mg ha^{-1}) using a GLM ANOVA. Main effects and their interactions were examined. Fuelbed bulk density was confounded with fuelbed age and fuel load treatments (see Findings); we therefore report bulk density values, but do not evaluate it as a dependent variable.

Fireline intensity was evaluated throughout the duration of flaming combustion using LOESS (locally weighted regression scatter plot smoothing) curve-fitting across replicated burns. While peak fireline intensity indicates the maximum energy output within one 5 second interval for each burn, the LOESS regression provides weighted average fireline intensities throughout burning across replicates.

Reviews of Fire Behavior and Effects

Our synthesis of fuels and fire behavior in masticated fuels was a review and meta-analysis, so no field data were collected. We used past and current mastication studies supported by the JFSP and published values for all analyses. In addition, we began writing a broad synthesis of the ecological effects of mastication, which we expect to complete in 2017.

IV. Key Findings

Long-term fuel dynamics following mastication

As our review indicated, a major area of uncertainty exists regarding the long-term dynamics of masticated fuels. Our extensive field study provides some answers and is a good model for research in other masticated systems.

In our survey of the 25 masticated fuels treatments in northern California and southern Oregon, fuels varied across sites widely from 12.1 Mg ha^{-1} to 91.9 Mg ha^{-1} and averaged 30.6 Mg ha^{-1}. Within masticated woody fuel loads, different fuel classes revealed contrasting patterns. 1-hour and 10-hour fuels differed across sites. The 1-hour fuel loads varied by two orders of magnitude, ranging from 0.7 Mg ha^{-1} to 26.6 Mg ha^{-1}, however the vast majority (19 of the 25 sites) were not statistically different from each other. The 10-hour fuels also varied widely, ranging from 5.0 to 55.9 Mg ha^{-1} across the 25 sites. 100-hour fuels were somewhat less variable than the other size classes, ranging from 1.3 to 13.3 Mg ha^{-1}, but still differed across sites. As is commonly found within masticated fuelbeds, 1000-hour fuels were somewhat rare and highly variable. 1000-hour fuels ranged from 0.1 to 21.5 Mg ha^{-1} at the 25 sites. Litter and duff followed similar patterns of substantial variation across study sites. Litter ranged from 4.8 to 22.0 Mg ha^{-1} while duff ranged the widest of any individual category from 1.7 to 68.3 Mg ha^{-1}.

Regression analysis demonstrated that total fuel loading was significantly and negatively related to time since treatment, as expected ($P < 0.05$, $R^2 = 0.22$). The negative slope suggested a global rate of fuelbed loss attributed to decomposition of ca. 5% yr^{-1} over the sixteen year chronosequence. Following the overall trend, time since treatment was also significantly and negatively related to 1-hour ($P < 0.05$, $R^2 = 0.26$) and 100-hour ($P < 0.05$, $R^2 = 0.17$) fuel loading, while 10-hour fuel loading only approached significance ($P = 0.05$, $R^2 = 0.17$). Linear models for the smaller fuel size classes generally yielded better fits to the observed data. Upon examining the fuelbed size class compositions of 23 masticated sites, the proportion of 1-hour woody fuels within fuelbeds declined with time-since-mastication ($P < 0.05$, $R^2 = 0.19$).

Woody and litter fuelbed depths averaged 7.3 cm (± 0.4 s.e.) and ranged from 3.9 to 12.5 cm, differing significantly ($P < 0.001$) among the 25 sites. Fuelbed depths were hypothesized to decrease as time since mastication increased, due to decomposition. However, a simple linear regression demonstrated a lack of a significant decrease in fuelbed depth in relation to time since treatment ($P = 0.19$). The depth of duff averaged 2.3 cm (± 0.6 s.e.) and ranged from 0.3 to 4.6 cm. Duff depth also differed significantly across sites ($P < 0.001$).

Specific gravity of fuels within each site was hypothesized to decrease as time since treatment increased. Surprisingly, no timelag size class measured (1-, 10-, or 100-hour fuels) differed in specific gravity across the 23 sites (P = 0.05, P = 0.50, and P = 0.32, respectively).

Changes in masticated fuels 2005 to 2014: Remeasured sites

In the seven remeasured sites (first measured in 2005/6, measurement repeated in 2014), total masticated woody fuel loads lost 20% of their mass over the 8 to 9 year period between sampling. 1-hour fuels decreased by an average of 7.1 Mg ha^{-1} which reflects a 69% reduction over the eight to nine year period compared to previously sampled fuelbeds, and all seven sites decreased significantly. The 10-hour fuels decreased in loading by 5.7 Mg ha^{-1}, corresponding to a 33% reduction in the previously sampled mass after the eight to nine years between sampling periods. While the sampling detected decreases in all sites, only 10-hour loadings at the SFR and WHI sites were statistically significant. In the 100-hour size class, no differences in loading were detected between 2005 and 2014 sampling efforts. Litter loading at the seven sites increased (presumably from overstory contributions since treatment) by an average of 2.8 Mg ha^{-1} with more than half of them statistically different.

In contrast to results from the extensive plot network (and as we hypothesized), specific gravity was markedly reduced across woody particle sizes at all seven remeasured sites. The specific gravity of 1-hour fuel particles decreased by 23% over a period of 8 to 9 years between sampling. Specific gravity declined significantly at all seven remeasurement sites ($t = 12.13$, $p < 0.001$). The specific gravity of 10-hour fuel particles also decreased by 20% over the eight to nine years between measurements; again, differences were significant at all seven remeasurement sites ($t = 12.91$, $p < 0.0001$). 100-hour fuels experienced a significant average decrease of 13% in specific gravity ($t = 2.93$, $p < 0.01$).

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

Effects of mastication on shrub responses

Intensive study

The two sites (Challenge (northern Sierras) and Whitmore (southern Cascade Range)) exhibited differential woody vegetation response to masticated treatments. Total shrub and small tree basal area did not differ among treatments at Challenge. At Whitmore, the mastication only and the mastication with prescribed fire treatments resulted in significantly lower combined shrub and small tree basal area than the control, and the lowest basal area occurred in the mastication and herbicide treatment. Average stem heights followed the same pattern at both sites. Stem density at Challenge was lowest in the mastication and herbicide treatment whereas at Whitmore mastication alone resulted in the highest stem density and the mastication and herbicide treatments resulted in the lowest density. Total shrub and small tree basal area was positively related to canopy openness in the mastication and prescribed fire treatment at Challenge, but not at Whitmore. Total shrub and small tree basal area was negatively related to overstory basal area at Challenge, but not at Whitmore.

Treatments significantly influenced species composition and diversity at the two sites. At Challenge, richness of native woody vegetation was highest in the mastication and prescribed burning treatment. At Whitmore, richness was highest in the mastication only treatment and lowest in the mastication and herbicide treatment, although richness was much lower overall at this site. We found significant differences in woody species composition among treatments at both sites and through our Indicator Species Analysis (ISA) we found certain obligate-seeding species to be significantly associated with the mastication and prescribed fire treatment at Challenge (*Ceanothus integerrimus*) and within the no-treatment control at Whitmore (*Arctostaphylos viscida*).

Extensive study

Reestablishment of woody vegetation was highly variable across our 25 study sites where heights ranged from 3.7 to 157.5 cm and cover ranged from <1 to 67% within masticated treatments. Reestablishing woody vegetation height was positively related to time-since-treatment. Average annual precipitation, canopy closure, and masticated fuelbed depth were not found to be significantly related to height growth. Woody resprouters tended to be taller than seeding species across all treatments. Species from the genera *Quercus*, *Arctostaphylos*, and *Ceanothus* were the most abundant within these masticated sites. Results from this study illuminate highly variable outcomes following mastication and highlight the need for individualized site-specific predictions of treatment longevity and maintenance needs.

Effects of masticated fuels treatments on pine growth and mortality

Masticated treatments and overstory growth

At Whitmore, changes in average tree diameter (QMDinc) were greatest within the mastication and herbicide treatment followed by mastication only, and mastication and prescribed fire. Growth of pines in all mastication treatments were significantly greater than the controls. On average, trees within the masticated treatments were also significantly taller than controls, however, canopy base heights did not differ among treatments. Average crown ratios were significantly different among all treatments and were closely correlated with QMDinc.

Effects of post-mastication prescribed fire on growth and mortality

The relationship between percent crown volume scorched and basal area increment for individual ponderosa pine followed a “goldilocks” pattern when adjusted for initial dbh. At low and high levels of crown scorch, pines had diminished growth relative to those that received intermediate levels of scorch.

Our earlier surveys of mortality three years post-prescribed fire revealed distinct differences between sites, with the stands at Challenge undergoing substantial mortality while the effects of fire were subtle at Whitmore. By years 8 and 9, cumulative tree mortality was only 6.5% at Whitmore, while mortality at the Challenge site was 41%. Subsequent mortality at both sites occurred between our sampling at Year 2 and our remeasurements in 2013.

Laboratory fire behavior with time-since-mastication

As our review illuminated, there had been no research on the effects of masticated fuelbed aging on fire behavior. Our study (Kreye et al. 2016a) compared similar fuels with 2, 4, 10, and 16 years since treatment and across 25, 50, and 75 Mg ha^{-1} loads. Maximum flame heights of the masticated fuelbeds ranged from 15 to 80 cm and peak fireline intensities from 31 to 138 kW m^{-1} across the 36 experimental burns. As expected, flame heights and peak fireline intensities were strongly correlated ($P < 0.001$, $r = 0.862$). Flaming and smoldering durations ranged from 8.7 to 21.3 min and 35 to 121 min, respectively. Fuel consumption across the chronosequence ranged from 51 to 97%.

Fuelbed age had a negative influence on maximum flame height ($P < 0.001$) and peak fireline intensity ($P = 0.004$), but positively affected smoldering time ($P = 0.010$) across all fuel loads. Flame heights were shorter in the two oldest (10 and 16 year) fuels compared to the youngest (2 year old) fuels. Four year old fuels also burned with taller flames compared to the oldest (16 year) masticated fuels and peak fireline intensities were greater in the 4 year old fuels compared to both the older (10 and 16 year) fuels. Although fuelbed age did not affect flaming duration ($P = 0.345$), these older fuels smoldered for approximately 50% longer than the most recently masticated debris. Fuelbed age did not affect fuel consumption ($P = 0.846$), which averaged 89%.

Flame heights and peak fireline intensities differed across all fuel loads ($P < 0.001$) with heavier fuelbeds burning with taller flames and greater fireline intensity. Flaming duration, however, did not differ among fuel loads ($P = 0.660$), but the lighter 25 Mg ha^{-1} fuelbeds smoldered for shorter durations and were less consumed compared to the heavier 50 and 75 Mg ha^{-1} fuelbeds ($P < 0.001$). No interactions were detected between fuelbed age and fuel load on flame heights ($P = 0.981$), flaming duration ($P = 0.910$), smoldering duration ($P = 0.269$), fuel consumption ($P = 0.591$), or peak fireline intensity ($P = 0.281$).

Fireline intensity throughout burning (based on LOESS regression curves) also trended toward diminished energy release in the older fuels across all three fuel load categories. The 4 year old fuels, however, consistently burned with greater intensity than younger 2 year old fuels. Similar results were apparent in peak fireline intensities observed during burning of the 50 and 75 Mg ha^{-1} loads.

Several major patterns emerged from this study. The increases in smoldering with fuel age was notable. We hypothesized that this pattern is due to the changes in fuel particle composition, likely the relative increase in lignin:cellulose with age. As pointed out in our review, this change may have important implications for emissions (both the duration and chemistry), an important unknown. Older woody fuels burned with lower fireline intensity; whether this is the result of the losses of 1-h fuels (as noted in our extensive field study) or changes in fuel particles (noted above), we don't know. As these residual woody fuels interact with recovering vegetation, particularly flammable shrubs, our longer-term projections of fire behavior in masticated fuels becomes less clear.

Effects of mastication on fire behavior

Our review and synthesis of fire behavior in masticated fuelbeds (Kreye et al. 2014a) revealed several emergent patterns and highlighted some pressing research needs. First, the fuelbeds generated by mastication are novel and complex. The irregularly shaped particles and the compact fuelbed (with bulk densities far exceeding typical woody fuels) alter ignition, flaming, and smoldering behavior. Total woody fuelbed loading varies widely across published studies from 5.6 to 189.4 Mg ha^{-1}. Loads tend to be concentrated in fine (1-, 10-, and 100-h) fuels, with exceptions in masticated slash. Little information was available on decay or fuelbed changes over long period (but see our new work below).

Fire behavior studies in masticated fuels were separated into laboratory and field investigations. Lab studies reported flame length variation from 0.12 to 1.7 m, generally increasing with average fuel depth. The irregular shapes of masticated particles were not clearly tied to differences in fire behavior. Rate of spread was found to vary with fuel moisture (i.e. faster in dry fuels) and not across a span of fuel load (varying from 10 to 30 Mg ha^{-1}). As in field studies, masticated fuels flame for longer and smolder for much longer than predicted. In field studies, flame lengths mirrored lab studies, ranging from 0.26 to 1.88 m. The relationship observed between fuel depth and flame length in lab studies did not hold in field observations. Rates of spread in field studies ranged from 0.06 to 5.9 m min^{-1}. Masticated fuels smolder for long durations, in several cases burning for over an hour. Smoldering of masticated wood was also linked to consumption of underlying residual duff. Across a diversity of lab and field studies, masticated fuels tended to consume > 90%, with variation ranging from 47 to 93+%. The review highlighted anecdotal observations of ember transport from and to masticated fuelbeds. There were few studies of field fire behavior and many of these were unfortunately contradictory. Some emergent patterns were that fireline intensity was linked to fuel moisture and loads in expected ways. The review highlighted the shortcomings in field measurements and potential mechanisms for the contradiction between field and lab studies.

Our review highlighted science and management needs for masticated fuels (further discussed below in Future Research Needs). The primary areas of need are: 1) characterizing masticated fuelbeds and their changes over time; 2) moisture dynamics; 3) fuel consumption and emissions (the latter a notable gap in our current literature); and combustion and fire behavior. These knowledge gaps hinder the adoption of mastication and raise questions over its efficacy and environmental effects.

As mentioned above, we also began a review of the ecological effects of mastication (Kreye et al. 2016b). Our initial review of this topic was focused on the southeastern US, but we are coalescing data and information from across the US. Most of these studies focus on the interactions between mastication and prescribed fire, but some also investigate mastication as a stand-alone fuels treatment. As with our fire behavior review, there is substantial variation from the limited observations to date. Soil heating in some studies reveal deep heating, while others suggest minimal heat effects on underlying mineral soil. The potential for burning masticated debris to influence nutrient availability is clear, but research results are scant. Studies of vegetation response in the southeast reveal a mixed response to plant diversity, but most showed changes in species composition. Our preliminary analyses of US-wide results reveal similar patterns. The mixed results again offer little clarity to managers deciding on appropriate fuels treatments and offer little when weighing alternatives.

V. Management Implications

Mastication is an increasingly utilized fuels management tool across many vegetation types. Managers across the US have questions related to its efficacy, longevity, and ecological effects. Our research fills some of those gaps and highlights persistent needs. We cover the needs in the **Future Research Needs** section below and highlight management implications here.

A persistent question from managers relates to the longevity of mastication treatments or *how soon to re-treat*? Our fuel loading data suggest that fine fuels (1- and to some degree, 10-hour fuels) decay most rapidly, considerable quantities remained for years following treatment. 1-hour fuels lost approximately 2/3 of their load over the first decade in our study; 10-hour fuels lost about half that. Larger fuels (100- and 1000-hour) remained at initial post-treatment levels after a decade. As fine masticated fuels are primary drivers of ignition and perhaps spread, their loss is notable. The fact that some fine woody masticated fuels persisted is worrisome, as is that the more coarse fuels remained. Coarse fuels are related to greater fire severity and have been implicated in substantial soil heating (Busse et al. 2005, 2010). In the sites we measured in northern California and southern Oregon, mastication alone left considerable fuel loads even more than a decade since initial treatment. In the small number of sites where mastication was followed by prescribed fire, the amount of fuel consumed equated to approximately a decade of decomposition.

Another aspect of treatment longevity is the recovery of shrub and small tree fuels. Our research revealed that in sites dominated by resprouting species (many of the shrubs in the region and several hardwood trees), the recovery period can be rapid. Resprouters quickly gained in height, perhaps as a response to the increases in light and concomitant decreases in competition. In a site where supplemental treatment by herbicide was done (Challenge), shrub and small tree recovery was substantially stalled. Sites with follow-up prescribed fire increased the density of shrubs (as in Kane et al. 2010), but diminished their stature. We anticipated that shading caused by residual trees in masticated sites would slow recovery, but these patterns were not as strong as we hypothesized. What is clear is that sites with resprouters will cause problems and abbreviate the efficacy of mastication treatments unless supplemental herbicides or prescribed fire are applied. Because sites vary so much, we don’t have a silver bullet prescription, but the resprouter story is an important finding.

Our synthesis of fire behavior in masticated fuels (Kreye et al. 2014a) and our early work on the ecological effects of mastication (Kreye et al. 2016b) highlight important unknowns for masticated sites. Both reviews highlighted many more questions than answers- there has been far too little research on large wildland fires and their interaction with masticated sites, we know little about the longer-term ecological effects beyond what we might expect from structurally similar silvicultural methods, and masticated fuels are truly novel. What we do know is that species matter from a fire behavior standpoint and that as they age, masticated fuels change in their fire behavior. Successful prescribed fires have reduced masticated fuel loads in several regions and under typical prescription windows. In some of these cases where crown scorch was minimized, subsequent tree mortality was moderated (i.e. < 10%). In sites where scorch was greater, overstory tree mortality could be much higher (ca. 30-50%). Much of this mortality was due to the small size/young age of the residual trees in relation to the level of crown scorch. Much remains unknown in this broad area of research.

VI. Relationships to Other Recent Findings and Ongoing Work on This Topic

Our research supports and extends other mastication research considerably. Previous work on fuel loading was limited to studies with few sites and short times-since-mastication (e.g., Hood and Wu 2006, Kane et al. 2009). Our research on fuelbed dynamics represents the longest time span covered (1-16 years since mastication), largest number of sites (25+), and our measurements are detailed beyond measures of loading. These data supplement our earlier understanding of the relationships between load and depth, highlight the relative longevity of coarse and fine fuels, and begin to develop links between rate of vegetation recovery, reproductive mode, and residual overstory cover. These are important advances in our understanding of how masticated fuels change over time.

There has been some study of vegetation response to mastication (e.g., Potts et al. 2010, Kane et al. 2010, Kreye et al. 2014b), but due to the youth of this treatment, the majority of these data have been short-term snapshots. Our work on shrubs in our extensive sites and in our longitudinal sites represent the longest term data on vegetation response to date. These data reveal that in the absence of supplemental treatments, sites with resprouting shrubs and trees can regrow rapidly, reducing the efficacy of mastication treatments. Where non-sprouters are more common and in more xeric sites, mastication can be more effective. These results add considerably to what is known about the ecological trajectories post-mastication.

There has been little work on how mastication and mastication combined with other traetments affects residual tree growth and mortality. Our early work on the topic (Knapp et al. 2012) predicted low probability of residual tree survival in masticated sites that burn under wildfire conditions. Observations of mortality following prescribed fire elsewhere (Reiner et al. 2009, Kobziar et al. 2009, Kreye and Kobziar 2015) reveal contrasting patterns, where in some cases, mortality is elevated and others, it is not. Our current work (Hamby et al. submitted) suggests that mastication alone or in combination with herbicides increases residual tree growth in comparison to unthinned controls. In masticated and burned sites, the story is more complicated- at low levels of crown scorch, trees did not grow well (presumably without any effects to competition); the same was true for heavy scorch (where they also suffered greater mortality). At intermediate scorch levels, we observed what we term a “goldilocks effect” where tree growth was maximized. Our current data and design prevented us from further evaluating this phenomenon. We suggest later in **Future Research Needs** that this avenue of research deserves further attention from the fire science community.

Fire behavior research in masticated fuels has not been addressed to the degree it warrants (Kreye et al. 2014a). Our lab research on fuel aging is a step toward closing this gap. Past work in the lab (Kreye et al. 2011) and in field settings (e.g. Bradley et al. 2005, Knapp et al. 2012, Kreye and Kobziar 2015) provide more information on potential and observed fire behavior in masticated fuels. Our review and synthesis (Kreye et al. 2014a) highlights remaining needs and the rationale for more intensive study of fire behavior in these novel fuels.

Our review and synthesis summarized the research on fire behavior in masticated fuels. This work was the first of its kind for mastication and in some ways represented a “preview” rather than a review. There remains much to learn regarding masticated fuels and how the diverse conditions generated by mastication influence wildland fire behavior and effects. See more on this topic below in **Future Research Needs**.

VII. Future Work Needed

This body of research highlights several pressing research needs for masticated fuels and sites. We summarize these into 4 primary needs: 1) effects of mastication on the intensity and effects of wildland fires; 2) ecological consequences of mastication and fire; 3) consequences of mastication on overstory tree resilience; and 4) the need for research on mastication across representative sites beyond the regions studied to date.

Effects of mastication on the intensity and effects of wildland fires

A need highlighted in our synthesis of masticated fuel fire behavior was the dearth of observations of wildfires and prescribed fires in masticated fuels. There has been some research on prescribed fires (e.g., Bradley et al. 2005, Knapp et al. 2012, Kreye and Kobziar 2015), but these have been primarily limited to narrow prescription windows with somewhat conservative fire behavior. The lessons from this small number of studies are substantial- some fires burn far in excess of predicted behavior, crown scorch exceeds predicted values by factors of 4-5, and soil heating underneath masticated debris can be substantial. Studies that evaluate fire behavior in wildfires or in experimental fires ignited under dry and windy conditions are lacking and sorely needed. Fundamental questions related to fire behavior in these fuels could be tackled in such a research agenda (Kreye et al. 2014a). We include here an excerpt from our review that details specific science needs for mastication (Table 4)⇨:

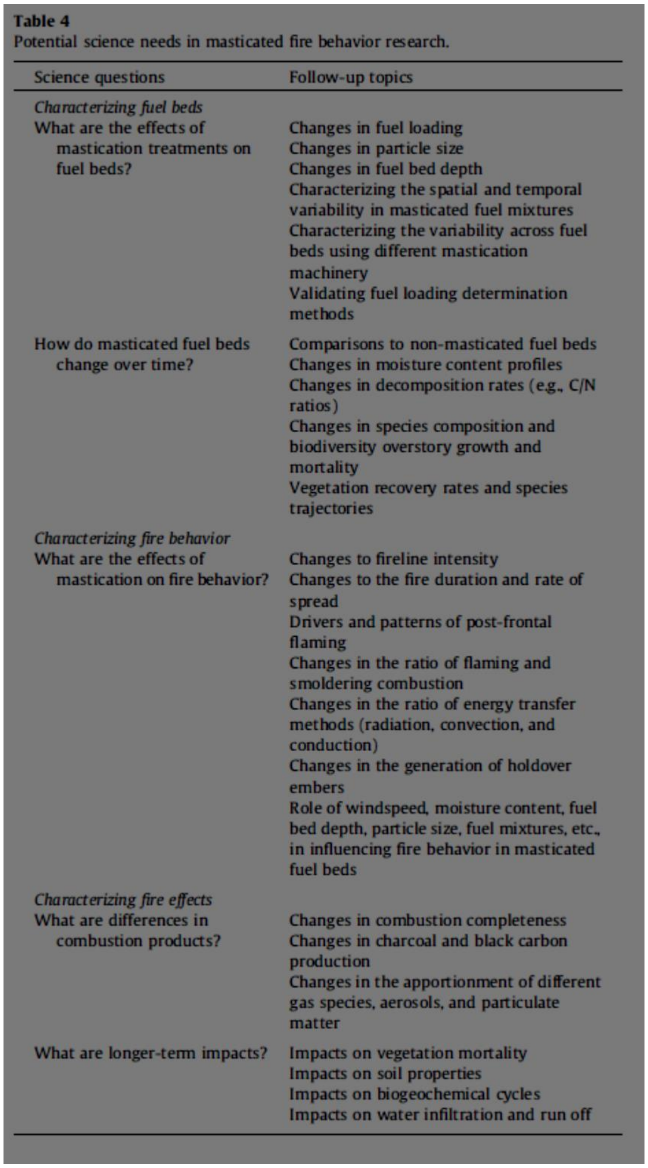

Table 4
Potential science needs in masticated fire behavior research.

Science questions	Follow-up topics
Characterizing fuel beds	
What are the effects of mastication treatments on fuel beds?	Changes in fuel loading Changes in particle size Changes in fuel bed depth Characterizing the spatial and temporal variability in masticated fuel mixtures Characterizing the variability across fuel beds using different mastication machinery Validating fuel loading determination methods
How do masticated fuel beds change over time?	Comparisons to non-masticated fuel beds Changes in moisture content profiles Changes in decomposition rates (e.g., C/N ratios) Changes in species composition and biodiversity overstory growth and mortality Vegetation recovery rates and species trajectories
Characterizing fire behavior	
What are the effects of mastication on fire behavior?	Changes to fireline intensity Changes to the fire duration and rate of spread Drivers and patterns of post-frontal flaming Changes in the ratio of flaming and smoldering combustion Changes in the ratio of energy transfer methods (radiation, convection, and conduction) Changes in the generation of holdover embers Role of windspeed, moisture content, fuel bed depth, particle size, fuel mixtures, etc., in influencing fire behavior in masticated fuel beds
Characterizing fire effects	
What are differences in combustion products?	Changes in combustion completeness Changes in charcoal and black carbon production Changes in the apportionment of different gas species, aerosols, and particulate matter
What are longer-term impacts?	Impacts on vegetation mortality Impacts on soil properties Impacts on biogeochemical cycles Impacts on water infiltration and run off

Ecological consequences of mastication and fire

Based on our own observations and via discussions with managers, we initiated a review of the ecological consequences of mastication and fire. Our initial attempt at this was focused on the southeastern US, where more mastication plus fire research has taken place (Kreye et al. 2016b). Following that effort, we have been working with other JFSP-funded groups (Idaho group led by P. Morgan; Colorado group led by M. Rocca and M. Battaglia; and Florida group led by L. Kobziar) to coalesce similar data on these responses. Our preliminary efforts have turned up many more questions than answers on basic research needs, including nutrient cycling, effects on native and non-native plants, consequences for wildlife habitat, and soil erosion (among many others). These are somewhat basic questions that hinder managers in their application of mastication over a wide diversity of sites and fuel conditions. This is a clear priority for future research.

Consequences of mastication on overstory tree resilience

Related to the prior need for additional research on ecological consequences of mastication is the need to better understand the consequences for residual overstory trees. Our work on ponderosa pine at two sites (Challenge and Whitmore; Hamby et al. *submitted*) are the most substantial to date. This lack of information is critical, as the residual overstory trees provide shade, retain fuel moisture, and help prevent the recovery of shrub and small trees that reduce the longevity of mastication and other fuels treatments (Agee and Skinner 2005). The status and resilience of these residual trees is made even more pressing with impending climate-caused stresses in dry western forests and more broadly. We see this gap as an important one for mastication and mastication followed by fire specifically, and in fuels treatments more broadly.

Research on mastication across representative sites beyond the regions studied to date

A pattern that we observed in our work on this and our previous JFSP-funded mastication grant was the dearth of research on mastication beyond a few well-studied regions. Mastication is not simply a dry western forest fuels treatment, its use is common in rangelands with a shrub component, in other western forests compositionally different than those we studied, and its use in eastern pine and hardwood forests is common. The lack of information in these sites is a notable shortcoming of mastication research. In our review of ecological effects of mastication in the Southeast (Kreye et al. 2016b), for example, we found few studies on the topic in spite of the frequency and extent of its use in that region. Our understanding of the literature leads us to question how much is really known about mastication beyond a few sites where relatively substantial work has been done.

VIII. Deliverables Crosswalk

Deliverable Type	**Description**	**Status**
Peer-reviewed publications (4)	Four submission-ready manuscripts covering: 1. *Long-term vegetation recovery following mastication* 2. *Long-term changes in masticated fuelbeds* 3. *Comparing short-term and long-term responses of fuels treatments in northern California* 4. *The effects of woody fuelbed aging on laboratory fire behavior*	(1) Thesis and *submitted* (2) Thesis and *in prep* (3) Thesis and *in prep* (4) In print
Webinar	Webinar to regional fuels managers (via *California Fire Science Consortium*)	Planned for Jan 2017
Updated website	Update our current PSW website with links to publications and updated photos of sites showing vegetation change since treatment (paired with pre- and original post-treatment photos)	Updated
On-line bibliography	On-line annotated bibliography of mastication research related to vegetation recovery, fuels and fire behavior	On-line Nov 2016. *EndNote* file can be further updated.
Symposium at conference	Organized symposium: *Longevity and efficacy of masticated fuels treatments*	Completed; International Fire Congress, San Antonio, TX (2015)
Presentation at manager-focused meeting	Presentation at a *Northern California Prescribed Fire Council* meeting on mastication and prescribed fire	Completed (Fall meeting, 2013)
Conference presentations (4)	Poster and oral presentations on results of this study	Completed (see below)
Manager-focused article (1)	Published paper on the longevity of mastication fuels treatments submitted to *Fire Management Today*	In progress- *planned 2017 submission.*
Field tour	Field tour of masticated fuelbeds in the Six Rivers NF	Completed

IX. Additional Deliverables Not Proposed

Deliverable Type	**Description**	**Status**
Peer-reviewed synthesis	Fire behavior in masticated fuels: A review (*Forest Ecology and Management* article)	Completed
Proceedings paper	Ecological effects of mastication (in *Biennial Southern Silvicultural Research Conference proceedings*)	Completed
Conference presentations (9)	Additional oral and poster presentations beyond the 4 proposed.	Completed
Master's theses (2)	G.W. Hamby, Mississippi State University (2015) W. Reed, Virginia Tech (2016)	Completed
Training module	RX-310 (NWCG) module, Murfreesboro, TN (2016)	Completed
University lectures	Mississippi State and Virginia Tech upper-division lectures and lab	Completed

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XI. Additional Reporting

a. Data Management- Forest Service Archive, November 2016
b. Deliverables (uploaded)
c. Bibliography on-line with EndNote file (uploaded)

XII. Final Report (uploaded)

XIII. Website

http://www.fs.fed.us/psw/topics/fire_science/masticated_fuels

XIV. Knowledge Transfer

a. Presentations list
    i. Oral

Hamby, G.W. 2013. Effects of mastication on ponderosa pine tree growth and mortality. Oral presentation at Department of Forestry, *Mississippi State University, Mississippi State, MS.*

Varner, J.M. and E.E. Knapp. 2013. The use of mastication as an ecological restoration tool. Oral presentation at the *Society for Ecological Restoration World Conference, Madison, WI.*

Varner, J.M., E.E. Knapp, J.M. Kane, J.K. Kreye, and H-S Han. 2013. Mechanical mastication as a fuels treatment tool- promise and challenges. Oral presentation at the *Northern California Prescribed Fire Council, South Lake Tahoe, CA.*

Kreye, J.K., N. Brewer, P. Morgan, J.M. Varner, A.M.S. Smith, C. Hoffman, and R.D. Ottmar. 2014. Fire behavior in masticated fuelbeds: A review. Oral presentation at the *Association for Fire Ecology/ International Association for Wildland Fire Large Wildland Fires: Social, Political, and Ecological Effects*, Missoula, MT.

Hamby, G.W., J.M. Varner, and E.E. Knapp. 2015. Effects of mastication and supplemental fuels treatments on growth and mortality of *Pinus ponderosa.* Oral presentation at the Special Session: Effects of mechanical mastication at the *International Fire Congress in San Antonio, TX.*

Reed, W.P., J.M. Varner, and E.E. Knapp. 2015. Fuel dynamics across a time-since-mastication chronosequence. Oral presentation at the Special Session: Effects of mechanical mastication at the *International Fire Congress in San Antonio, TX.*

Kreye, J.K., J.M. Varner, J.M. Kane, L. Kobziar, M. Rocca, M. Battaglia, and E.E. Knapp. 2015. Ecological effects of mastication- a synthesis. Oral presentation at the Special Session: Effects of mechanical mastication at the *International Fire Congress in San Antonio, TX.*

Kreye, J.K., J.M. Varner, E.E. Knapp, and J.M. Kane. 2015. The consequences of fuelbed aging on laboratory fire behavior of masticated fuelbeds. Oral presentation at the Special Session: Effects of mechanical mastication at the *International Fire Congress in San Antonio, TX.*

Varner, J.M. 2016. Mechanical mastication as a fuels treatment: fire behavior and ecological effects. Presentation at RX-310 in Murfreesboro, TN.

ii. Posters

Hamby, G.W., J.M. Varner, and E.E. Knapp. 2013. Effects of mastication on ponderosa pine tree growth and mortality. Poster presented at *Southeastern Natural Resources Graduate Student Symposium*, Starkville, MS.

Hamby, G.W., J.M. Varner, and E.E. Knapp. 2013. *Pinus ponderosa* growth and mortality following mastication in California, USA. Poster presented at *Mississippi State University Graduate Student Forum, College of Forest Resources, Mississippi State, MS.*

Reed, W.P., J.M. Varner, and E.E. Knapp. 2013. Long-term changes in masticated fuelbeds in northern California and southern Oregon. Poster presented at *Mississippi State University Graduate Student Forum, College of Forest Resources, Mississippi State, MS.*

Hamby, G.W., J.M. Varner, E.E. Knapp, S.D. Roberts, and B. R Frey. 2014. The effects of mastication and supplemental fuels treatments on residual pine growth and mortality. Poster presented at the *Association for Fire Ecology/ International Association for Wildland Fire Large Wildland Fires: Social, Political, and Ecological Effects*, Missoula, MT.

Reed, W.P., J.M. Varner, and E.E. Knapp. 2014. A bibliography of mechanical mastication. Poster presented at the *Association for Fire Ecology/ International Association for Wildland Fire Large Wildland Fires: Social, Political, and Ecological Effects*, Missoula, MT.

iii. Panels

The fire behavior and ecological effects of mechanical mastication. 2015. Participants: J.M. Varner, J.K. Kreye, M. Battaglia, B. Keane, and P. Morgan. A panel discussion at the Special Session: Effects of mechanical mastication at the *International Fire Congress in San Antonio, TX.*

iv. Symposia

The fire behavior and ecological effects of mechanical mastication. 2015. Co-Sponsors: J.K. Kreye, J.M. Varner, M. Battaglia, and E.E. Knapp. Special Session *International Fire Congress in San Antonio, TX.*

b. Publications list

i. Published

Kreye, J.K., N.W. Brewer, P. Morgan, J.M. Varner, A.M.S. Smith, C.M. Hoffman, and R.D. Ottmar. 2014. Fire behavior in masticated fuels: A review. *Forest Ecology & Management* 314: 193-207.

Kreye, J.K., J.M. Varner, J.M. Kane, E.E. Knapp, and W.P. Reed. 2016. The impact of aging on laboratory fire behaviour in masticated shrub fuelbeds of California and Oregon, USA. *International Journal of Wildland Fire* 25: 1002-1008.

Kreye, J.K., Varner, J.M., and L.N. Kobziar. 2016. Mechanical mastication as a fuels treatment in southeastern forests. Pages 198-205 in *Proceedings of the 18th Biennial Southern Silvicultural Research Conference.* eGTR-SRS-212. USDA Forest Service, Southern Res. Sta., Asheville, NC.

ii. In progress

Hamby, G.W., J.M. Varner, E.E. Knapp, S.D Roberts, B.R. Frey, and R.F. Powers. Long-term ponderosa pine growth and mortality following masticated fuels treatments in northern California, USA. Submitted to *Forest Ecology and Management* 07 November 2016.

Reed, W.P., J.M. Varner, and E.E. Knapp. Long-term changes in masticated woody fuelbeds in northern California and Oregon, USA. To be submitted to *International Journal of Wildland Fire.*

Varner, J.M., J.K. Kreye, E.E. Knapp, S. Drury, J.M Kane, G.W. Hamby, and W.P Reed. Mechanical mastication as a fuels treatment- promise and challenges. To be submitted to the Pacific Southwest Research Station as a *USDA Forest Service General Technical Report*.

c. Graduate Education list

Hamby, G.W. 2015. Fuels treatment longevity of mechanical mastication and growth response of ponderosa pine (*Pinus ponderosa*) in northern California. Mississippi State University, Mississippi State, MS. 65 pp.

Reed, W.P. 2016. Long-term Fuel and Vegetation Responses to Mechanical Mastication in northern California and southern Oregon. Thesis, Virginia Tech, Blacksburg, VA. 88 pp.

d. Use in courses

FOR 3231 *Forest Fires* Mississippi State University (2014)

Material and results used in lectures for Fuels management challenges.

FREC 4153 Advanced Fire Ecology & Management Virginia Tech (2015)

Material and results used in lectures for Fuels management challenges.